Specification of a Standardized Listening Room for an Expert Listening Panel

Audio Engineering Project Report

by

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Abstract

Within this work a listening room was specified which fulfils one of the current standards for the assessment of audio systems. The aim of this work was to determine the inner life of the target room to meet the requirements of the chosen standard. First, former similar listening room projects were searched for. Subsequently, the major currently existing standards for the assessment of audio systems and sound material were quoted and compared, thereupon the most suitable was chosen. The choice that was taken was the ITU-R BS 1116-1 standard because of the small floor area of the existing target room at the JOANNEUM RESEARCH site in Schießstattgasse 14b/I, 8010 Graz, Austria.

To be able to simulate the room's acoustics, the its geometry was implemented in the commercially available software CATT Acoustic®. The calibration of the simulation was then accomplished with values obtained by a thorough measurement of the empty target room by employing the commercially available software WinMLS. Afterwards, the optimization process could be started. The chosen standard, however, primarily defines the reverberation time of a listening room. Thus the virtual room was equipped in order to attenuate the sound field in accordance with the standard's requirements.

As a result, two solutions for a listening room are presented. One variation was implemented using the existent step in the ceiling. The second variation omits the step. Both approaches yielded quite good reverberation time results when using slightly different material for each of the rooms. In addition, a list of the required acoustic material, furniture and sound system is given along with exact planing on how and where to place them. Moreover, an estimate of the costs for the entire fixture is presented.

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1 Introduction

The auditory sense is highly important to any human being. Even though a lot of people tend to forget about their sense of hearing, it is there all the time influencing our daily life. We can close our nose and eyes, look away at times but rarely can we completely close our ears to the world surrounding us. We owe a lot of pleasure to our hearing system, in particular, when listening to music or simply to the sound of nature. In the same way, we are prone to a number of disturbances, caused by all kinds of noise and other acoustical disturbances. This ability of our ears to differentiate between even the smallest changes in sound makes them indispensable for the assessment of acoustic equipment and material.

In spite of the immense technological advances of acoustic reproduction devices and measuring instruments throughout the last 20 years, the human ear still possesses the supremacy of being the number the leading instrument when it comes to acoustical tests of any kind. An objective measuring method can never judge and interpret the given acoustic situation as reliably as the 'instrument' ear.

However, the ear can also be impaired easily. The acoustic environment and sound reproduction systems have a great influence on how sound is being perceived by the listener, albeit subconsciously. In order to obtain consistency of the results yielded by the ear, it is necessary to keep control of those few influencing factors one can control, namely the acoustics environment, i.e. the listening room, and the sound system reproducing the material under test. This awareness is essential to anyone who seriously wants to work with the human ear as a measurement tool.

In these days of international collaboration in acoustics, the need for comparable, reliable and reproducible measurement results are more important than ever. Results that have been obtained in one part of the world might need to be equal to those obtained in another part of the world. If the measuring conditions are not the same, the reviewing an crosschecking would not make any sense since the results would not be comparable at all.

For this reason, many organizations have devoted themselves to finding internationally valid recommendations for specific conditions under which to test sound devices and material (see Section 2.3). The problem in this task however, is still the persistent lack of thorough understanding of the processes going on in sound propagation. The sound field as such, up to now, cannot be described completely and uniquely by acoustic parameters alone. For these reasons, the recommendations, described in Section 2.3, only contain recommendations concerning room geometry and electro-acoustic characteristics of sound devices, some more stringent than others (according to [8]).

In spite of the above said, the reader has to be aware of the fact that not only the listening room and sound reproduction devices alone influence the results obtained during the listening test. There are other factors, mainly of psychological nature, that greatly affect the judgment process of the listeners. This, though, is not subject to this work. For further reading see standard literature (e.g. [13])

1.1 Motivation

The Advanced Audio Processing (AAP) Project is a cooperation between JOANNEUM RESEARCH, the Institute of Electronic Music and Acoustics (KU Graz), the Institute of Signal Processing and Speech Communication Laboratory (TU Graz), Philips Austria GmbH, AKG Acoustics GmbH and ATRONIC Austria GmbH. Its major research program comprises acoustic multiple-input multiple-output (MIMO) systems, signal enhancement and perceptual optimization. These research topics allow the industrial and scientific partners to use the results in a variety of applications that can be found in the automotive market, in professional audio and communication technologies, and in the entertainment industry. The expected results can be implemented in systems for in-car-communications, dictation and teleconferencing, in professional headphones and loudspeakers, and casino gaming machines.

As part of the AAP project, the work package ‘Expert listening panel for sound quality evaluation’ focuses on the problems and challenges of assessing professional audio applications and equipment. While a lot of test centres exist for objective measurements, the lack of facilities for the realization of subjective listening tests makes it difficult to obtain repeatable and reproducible results. The fields of application and the products being tested in the facility which is subject to this work are:

- Sound quality of microphones for studio and automotive applications; from in-ear headphones to professional studio headphones, etc.
- Spatial attributes of sound fields
- Speech quality (e.g. of voice recorders during playback)
- Data representation through sound (e.g. assessment of sonified signals)

The basic problem with listening tests in general is the complex interaction between stimulus and the resulting sensation. In most cases, the scientific interpretation of such stimuli is only feasible by interrogating a bigger group of listeners. If the obtained results are to be statistically representative for the entirety of all possible listeners, the group of test listeners must be chosen carefully. For this purpose, a group of professional listeners (→ Listening Panel) is needed in order to yield consistent results. Moreover, standardized listening test interrogation structures need to be maintained to achieve a repeatable assessment procedure. The task of selecting and training a group of professional listeners and the challenge of implementing a standardized assessment procedure has been distributed among the research partners and is not subject to this work.

It would be desirable, especially for the industry, to create a facility that is as neutral as possible, which should then receive tasks from the industry. As a final goal, it would be desirable to obtain a test location that is able to deliver some kind of certification similar to those of Dolby or THX at the moment.

1.2 Objective

In the course of this project and the work package, JOANNEUM RESEARCH was assigned with the task of specifying and constructing a room that would fulfil all the desired requirements stated above. Furthermore, the room should be consistent with one of the international standards for listening room environments that are available at present. The room of choice to become this reference listening room is located at the JOANNEUM RESEARCH site in Schießstattgasse 14b/I in 8010 Graz, Austria.

This project report describes the specification and simulation of such a facility. The room, with a floor area of about 30 m², is to be designed according to one of the current international standards concerning listening rooms and assessment of sound material. The conditions stated in one of these recommendations should preferably be attained by the whole sound field of the room and the sound system used.

The result of this work will finally be a set of clear instructions on how to construct the room to meet all requirements stated in the following Sections. The work shall contain a specification of the sound system, furniture and acoustic material needed as well as a detailed list of the aforementioned, along with the instructions on how and where to place them. In addition, an estimation of costs for all required entries will be issued.

1.3 Overview

The project report is structured as follows: Section 2.1 gives a historical outline of the existing professionally used listening rooms in Europe that have been constructed over the last 20 years. An overview and comparison of current internationally valid standards for listening room specifications can be found in Section 2.3. Furthermore, a discussion on the suitability of those standards for the cause of this work is given. In addition, Chapter 2 contains the justification why a certain standard has been chosen above the others.

Chapter 3 describes the specification process of the listening room. The current state, i.e. room geometry, etc. are described (see Section 3.1.1) as well as the desired target state for the listening room, i.e. what conditions should the room fulfil when finished (see Section 3.1.2). On the basis of the simulation with the commercially available software CATT Acoustic®, the acoustic properties of the room at hand will be optimized. This part of the work is described in Section 3.2. Finally, Section 3.3 formulates the construction measures necessary to obtain an optimized listening environment according to the standard chosen.

The appropriate sound system and fitting furniture in accordance with the standard chosen are specified in Section 3.4. An estimation of costs for the sound system, furniture and all necessary acoustic treatment are given in Chapter 4.

A short discussion of the results obtained in the simulation compared to the requirements from the chosen standard can be found in Chapter 5 as well as a prospect to the further steps necessary to implement the proposed and simulated reference listening room.

2 Methods

2.1 Existing listening rooms

In this Chapter a short summary of already existing listening rooms using different standards, mainly EBU [14, 15] and ITU [1], is given along with a chronological outline. Furthermore, the specific features of each room will be presented. Essential to all of the presented examples is the need to maintain objectiveness as best as possible with respect to listening tests.

2.1.1 “A new type of listening room”

The chronologically first paper chosen by the author was written by Japanese scientists in 1982. In their paper, Ishii and Mizutani [2] presented, at that time, a new type of listening room. The authors stated that it can provide for frequency flat reflections by using a combination of absorptive and reverberant elements in the room. Fig. 2.1 shows the floor plan of the proposed room.

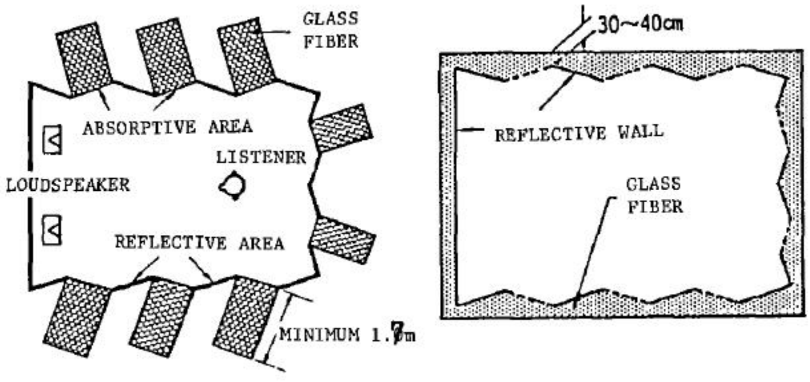


Fig. 2.1: Basic construction of the listening room (left) and its space saving alternative (right) [2]

The room has been designed upon problems occurring in conventional listening rooms of the time, such as [2]:

- The frequency response of the reflected wave is not flat
- The incoming direction toward the listener.
- The low frequency sound tends to become "boomy".

- The frequency range is too narrow for hi-fidelity listening.
- Design is complicated and time consuming.

The room presented is said to have different, better characteristics so as to avoid the problems mentioned above, which are:

- Every reflecting sound is independent of frequency.
- Even a short pulse preserves its wave form.
- The rigid wall does not vibrate.
- Easy to design and build.
- The reverberation time of the room can be changed linearly independent of frequency simply by changing the area of rigid wall by using a "sliding reflector."

An example of such a room is also presented [2].

2.1.2 Finnish Broadcasting Company

The Finnish Broadcasting Company designed and constructed a reference listening room in 1984 for a special quality listening group to assess and develop the quality of (music) recordings and technical equipment [3]. The method applied was developed by the International Radio and Television Organisation OIRT (for further references see [3]). The OIRT Recommendations were the only internationally unified methods existing at the time but, being quite imprecise, Borenius and Korhonen defined more detailed design goals which suited the room of the Finnish Broadcasting Company better.

The room is innovative due to the 8-cornered shape being used. The corner trap construction is an excellent background for free standing monitors. Loudspeakers built into the wall can be used as well. Fig. 2.2 shows the floor plan of the listening room at the Finnish Broadcasting Company. Its floor area adds up to 58 m², the volume amounts to 189 m³. [3]

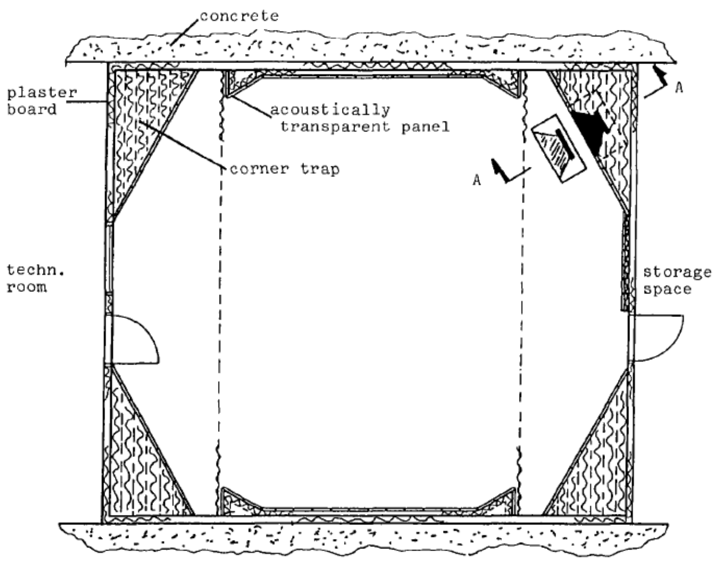


Fig. 2.2: The floor plan of the FBC room with corner traps [3]

2.1.3 GDR Broadcasting

Like the Finnish Broadcasting Company (Section 2.1.2), the German Democratic Republic Broadcasting sought to find a new set of Recommendations for reference listening rooms in 1988. Although a number of internationally accepted documents had already existed by then, e.g. composed by the OIRT and the CCIR, predecessor of the ITU-R, (see [4] for references), these Recommendations were not satisfying as they contained too many varying opinions. [4]

Based on the multitude of recommendations by the CCIR, the UER, the OIRT and the Nordic Broadcasting Companies, Gerhard Steinke formulated a detailed proposal for a Recommendation, giving clear instructions on how to design a listening room. [4]

2.1.4 BBC Research & Development Department

One of the institutions devoting themselves elaborately and profoundly to the subject of reference listening room design is the BBC Research & Development Department in Tadworth, UK. Robert Walker has worked on solving the problems arising with the design of listening rooms, focusing on dealing with early reflections. During his research, quite a number of listening rooms and control rooms were built for the BBC which also included the new approaches concerning reverberation field design for both two-channel and multichannel sound. Although the rooms presented in the following were both created to be control rooms, one can still consider a control room to be a listening room with an additional large table in it.

Room Acoustics for Stereophony

The rise of stereophony also brought up the awareness of how important the reflections arriving at the listener up to 20 ms after the direct sound were. These caused significant distortions of the perceived sound as well as image shifts. In the course of this realisation the acoustics treatment applied to the rooms grew increasingly, leading to acoustically ‘dead’ rooms with reverberation times of about 0.15 s. Not only were these rooms expensive to construct but they were also quite oppressive to work in. [9, 10]

The motivation for designing this room in the first place was to obtain a stereophonic image that is less dependent on the room and at the same time to ensure a mean reverberation time of 0.35 s. This objective was to be achieved by a technique called ‘Controlled Image Design’, developed by Walker in 1993. [9]

The main idea of this new concept was to redirect the first reflections away from the reference listening position, i.e. tangential to an imaginary circle around the listener, so as to sharpen the stereophonic image while at the same time maintaining an environment that is comfortable to work in. This was achieved by placing angled, reflecting surface in front of the listener and behind the loudspeakers. Fig. 2.3 shows a sketch of the proposed room. The room area is 33.8 m^2.

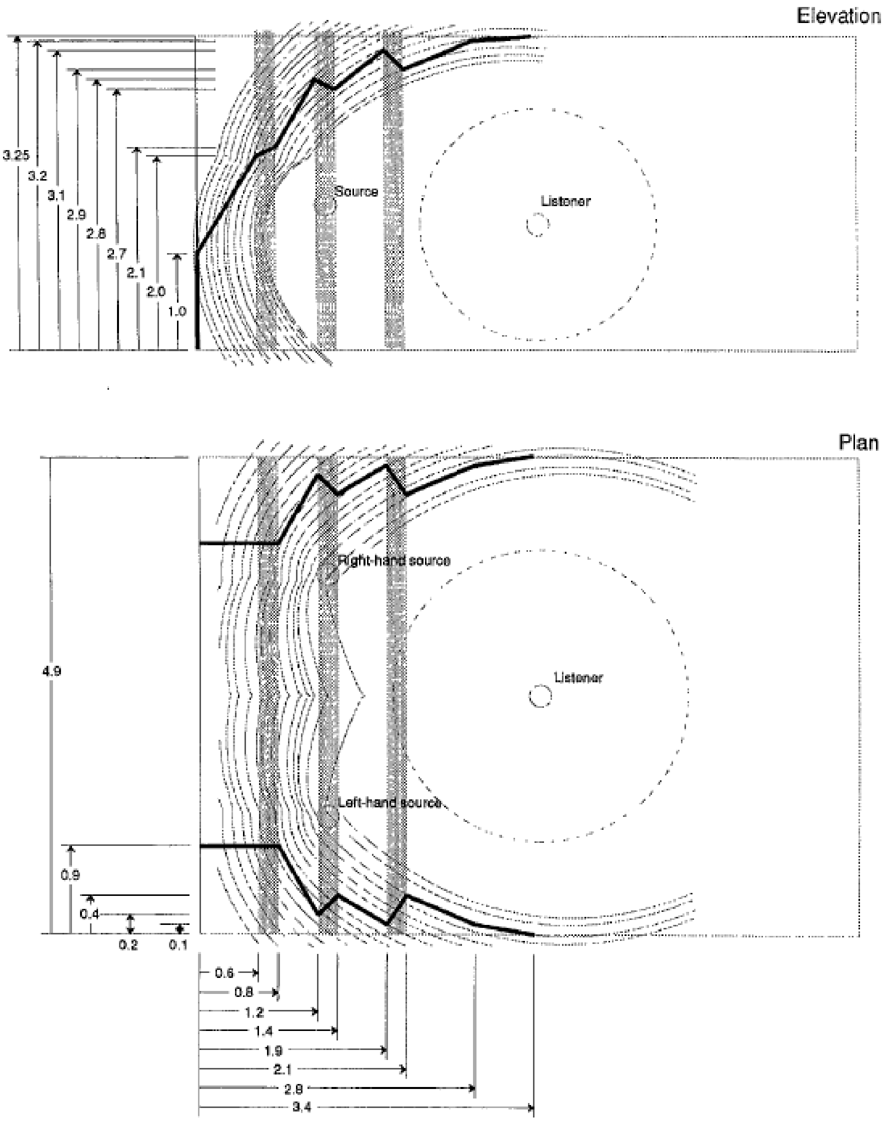


Fig. 2.3: Design sketch for the completed test room at the BBC R&D Department [9]

The practical part about this particular approach is that surfaces which up to now have been considered to be a problem, i.e. reflecting surfaces of control room windows etc., now become beneficial to the overall room concept as the surfaces used in the design must of necessity be acoustically hard [9]. Details of this approach can also be found in the according BBC Tech Report by Walker [10].

Results of the early reflections measurements in the first 'Controlled Image Design' installation can be found in [11] and more detailed in [12].

Room Acoustics for multichannel sound

The approach for this proposed room is very similar to the one described above for two-channel stereophony. The room was constructed in accordance with the ITU [1] and EBU [14 15] standard and was essentially completed in 1997.

For the control of the first and second order reflections a few simplification considerations were made. The second order reflections can be ignored on the basis of time delay and the natural attenuation with distance. With the proposed 2 m loudspeaker/listener distance, reflections with a path longer than 6.43 m will be attenuated by at least 10 dB relative to the direct sound already by spreading loss. The remaining few first order reflections are then dealt with adequate angled absorptive and reflective acoustic elements on the wall. Fig. 2.4 shows the designed room with its completed wall design (half room) with angled panels, shallow and deep acoustic treatment and the 'circle of exclusion' with a radius of 1 m. The room's dimensions are 6.67 m times 4.94 m times 3.2 m, which yields a floor area of 33.4 m² and a room volume of about 107 m³. [7]

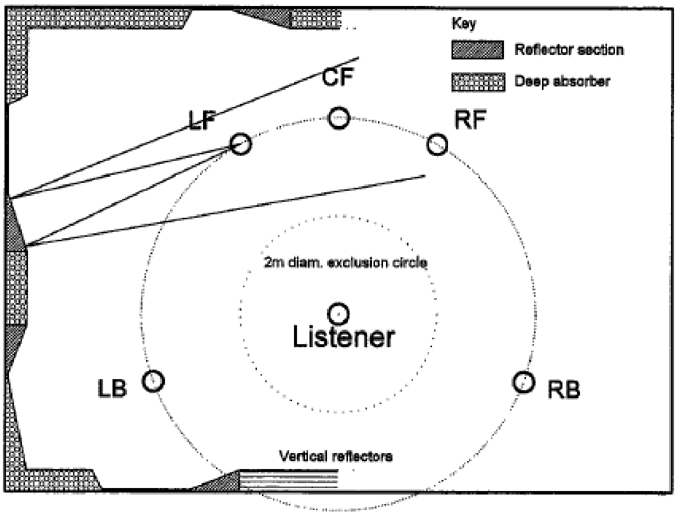


Fig. 2.4: Layout of the reflecting panels and acoustic treatment showing control of the reflections from Left-Front loudspeaker [7]

The deep treatment was constructed of a BBC home made absorber [16], consisting of 180 mm deep metal studs filled entirely with medium-density glass wool, covered in a 1 mm thick steel sheet to provide low and high frequency absorption, respectively. The shallow treatment consisted of 3 mm perforated hardboard over 25 mm glass wool for selective mid-band absorption around 400 Hz. [7]

2.1.5 Helsinki University of Technology

Out of the need of having research projects where subjective assessment was essential, the Helsinki University of Technology, Laboratory of Acoustics and Audio Signal Processing, built a reference listening room facility in 1997. [5]

The paper describes and compares several standards concerning room geometry, reverberation time and background noise. Furthermore, it provides a discussion on various simulation methods and programs as well as different reverberation time measurement systems. The listening room described in the paper, as it was decided, should conform to the ITU-R BS 1116 standard (NOTE: Not to be confused with ITU-R BS 1116-1, which is the 1997 revised version of the ITU standard from 1994 [13]).

The authors give quite an accurate description of the design procedure for the room concerning absorption panels, heating, ventilation and air condition, etc. Included in the specifications was also a modified version of the Schroeder diffuser developed by the authors of [5]. Fig. 2.5 shows the floor plan of the designed listening room. Its floor area is 35.6 m²; the volume adds up to 96 m³. [5]

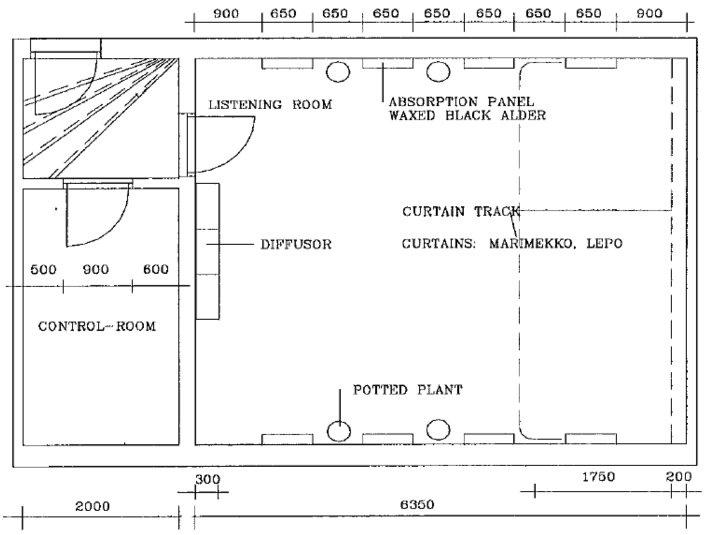


Fig. 2.5: Floor plan of the HUT listening room and control room [5]

2.1.6 Hungarian Radio Budapest

The publication of the paper about the Hungarian Radio reference listening room from 1998 is the first reference not only mentioning two-channel stereophonic but also multi-channel stereophonic as an important issue that was found in the literature by the author. [6]

Fig. 2.6 shows the floor plan and a 3-dimensional view of the presented listening room, as well as the location of sound sources and the reference listening point. Its floor area amounts to 55 m²; the volume is 267 m³. [6]

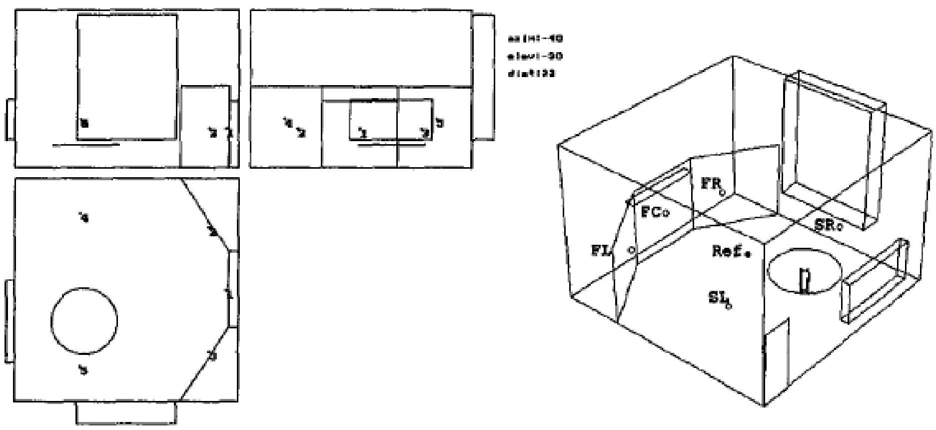


Fig. 2.6: Floor plan and 3D view of the listening room at the Hungarian Radio in Budapest [6]

For the existing room, into which the listening room was to be built, the EBU 3276 standard [14, 15] was considered to be the most suitable. The evaluation of its room acoustics includes the sound field parameters specified by the EBU Recommendation [14, 15]. The room was previously modelled by Finite Element Method using the commercial software SYSNOISE for simulation. Fig. 2.7 shows the placements of acoustical elements in the described listening room. [6]

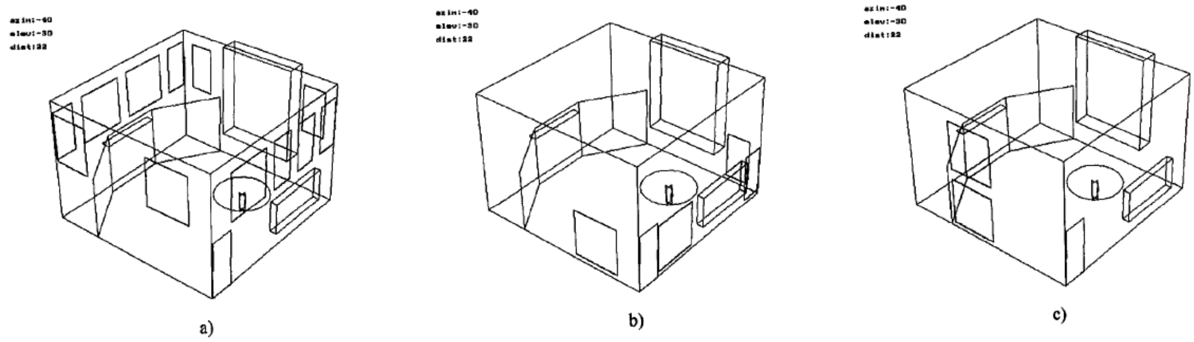


Fig. 2.7: Placement of different acoustical elements in the HRB Room. [6]
a) Low Frequency absorbers; b) Diffusers; c) Wide-band absorbers

2.1.7 University of Surrey

The idea behind 'The Active Listening Room Simulator' project, realized at the University of Surrey in 2001 and 2002, was to simulate different artificial sound fields by strategically arranging multiple active sound sources around the listening position. The advantage of such a set up is the possibility of carrying out listening test in different acoustic environments and thus investigating the effect of change in listening conditions on the results of listening tests. [17, 18, 19]

The experiment was installed in an ITU-R BS 1116-1 [1] conformant listening room at the University of Surrey. The floor area amounts to 39.17 m²; the room volume is 97.94 m³.

Active Listening Room Simulator - Part 1

The first part of the 'Active Listening Room' publication series deals with a one loudspeaker set up (see Fig. 2.8) along with flat panel DML loudspeakers for the active shaping of the sound field. The DML loudspeakers also serve as deflector panels only when inactive. [17]

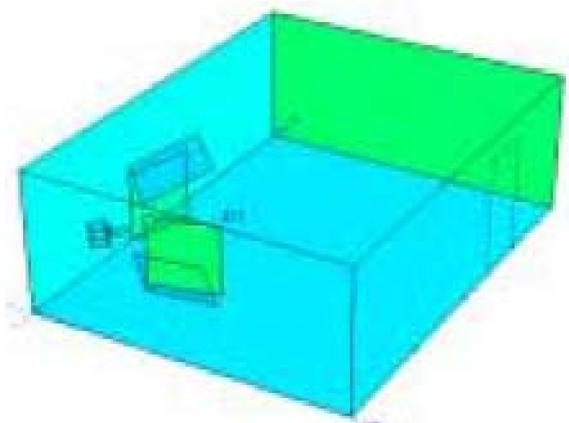


Fig. 2.8: CATT Acoustic ® model plot of the experimental set up with one loudspeaker [17]

The set up was based on the computer model produced by the commercially available software CATT Acoustic ®, which optimized the angles and positions of the panels to create a reflection free zone and to predict the according reflection patterns within the first 20 ms. The measuring results showed that a reflection free zone around the listening position could be established and that individual DML panels could generate discrete artificial reflections within this reflection free zone. [17]

To measure the Energy-Time-Frequency responses of all the set ups a MLSSA (Maximum Length Sequence System Analyzer) measurement system was used.

Active Listening Room Simulator - Part 2

Part two of the project expanded the set up from ‘Part 1’ into a two-speaker, stereo configuration. Again, the optimum angular panel setting in order to create a geometric boundary to force the early reflections away from the listening position was determined using CATT Acoustic ® [18]. Fig. 2.9 shows the 3D plot of the room.

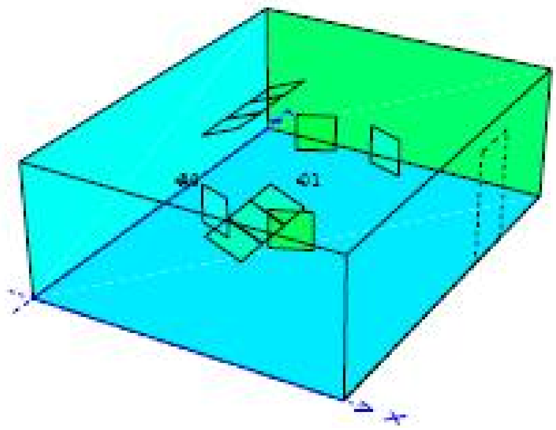


Fig. 2.9: 3D view plot of the panel arrangement [18]

A0 = left speaker; 01 0 receiver

As an additional aid, a ray tracing diagram was produced to identify the main paths of significant reflections from the left speaker, as seen in Fig. 2.10.

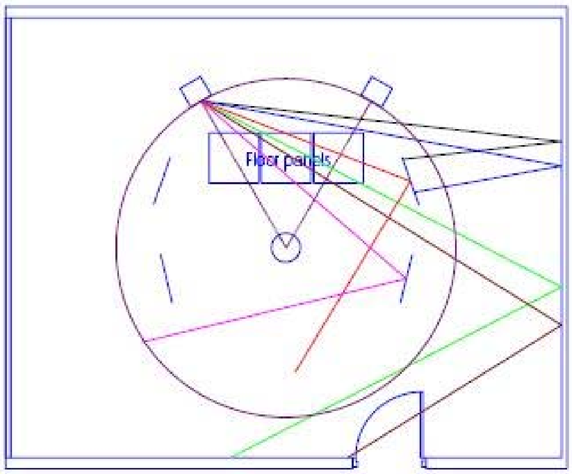


Fig. 2.10: Ray tracing diagram of panel arrangement [18]

Active Listening Room Simulator - Part 3

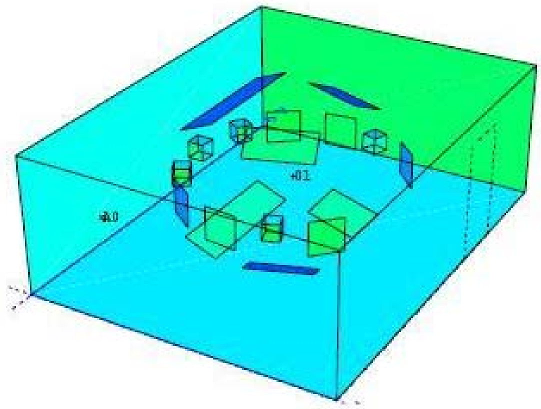


Fig. 2.11: 3D view plot of the five channel loudspeaker arrangement [19]
A0 = left speaker; 01 = receiver

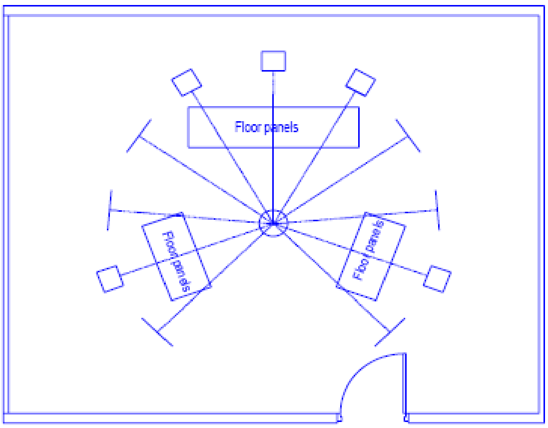


Fig. 2.12: Model of the ideal reflection path for five speaker arrangement [19]

Part 3, the final phase of the experiment, involves a five channel source loudspeaker and an arrangement containing sixteen DML panels. As before, the angles and positions of the panels were determined by CATT Acoustic® to find their optima (see Fig. 2.11). Fig. 2.12 shows the sketch of an ideal reflection path model also used for determining the main paths of significant reflections from the source loudspeaker in the symmetrical listening arrangement. [19]

2.2 Room acoustics

The following sub-Sections will give a short outline of those acoustic parameters that are most important for the comprehension of this work.

2.2.1 Electro-acoustic features

Frequency response of a loudspeaker

The frequency response serves as a means of describing the transfer behaviour of a dynamic system (in this case the loudspeaker).

Directivity index

The directivity index is defined as the logarithm of the directivity factor.

$$d(\varpi) = 10\lg \frac{S}{\oint_S \Gamma^2(\omega) dS} \text{ dB} \quad \text{with e.g. } S=4\pi r^2 \text{(surface of a sphere)}$$

$d(\varpi)$ is the difference between the SPL of a sound source measured on the main axis (0°) at a distance r and the SPL, measured at the same position, of an imaginary omni-directional source radiating the same acoustic power. [20]

Non-linear distortion

In context of the ITU standard, the non-linear distortion describes the harmonic distortion component of the loudspeaker when operated with a constant voltage input signal, producing a certain sound pressure level. [1]

Transient fidelity

The transient fidelity refers to the decay time of a sinusoidal tone burst produced by the loudspeaker. [1]

Dynamic Range

The dynamic range typically describes the range from the quietest to the loudest sound produced.

2.2.2 Room acoustic features

Reverberation time

The reverberation time T_{60} is described as the time where the sound level of the reverberation decreases by 60 dB. [20] The same is valid for the reverberation time T_{30} where the sound level only needs to decrease by 30 dB.

Early reflections

Reflections caused by boundary surfaces of a room that reach the listening area within a time interval of 15 ms after the direct sound. [1]

Late energy

Late energy describes the sound energy that reaches the listener more than 15 ms after the direct sound. [1]

Operational room response

The operational room response is defined as the one-third octave frequency response of the sound pressure levels. The frequency responses should cover the frequency range of 50 Hz to 16 kHz. [1]

Operational sound pressure level

The reference listening level is defined as the preferred listening level, produced with a given measuring signal at the reference listening point. It characterizes the acoustic gain of the reproduction channel so as to ensure the same sound pressure level in different listening rooms. [1]

Definition (D50)

Early energy increases the clarity of a signal. With speech, this part of the total energy lies within the range of 50 ms after the direct sound. The definition gives the ratio between the energy reaching the listener during the first 50 ms and the total energy. [23]

$$D_{50} = \frac{W_{0...50}}{W_{total}} = \frac{\int_0^{50ms} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \qquad [\%]$$

Clarity (C50)

The Clarity C50, having a greater practical importance, can easily be derived from the Definition. It gives the difference between the levels of the sound energy reaching the listener before and after 50 ms time, respectively.

$$C_{50} = 10\log\frac{W_{0...50}}{W_{50...\infty}} \qquad \text{[dB]}$$

The desirable level of C50 for good intelligibility lies within the range of 2 dB>C50>-3 dB. Above 2 dB the intelligibility is very good; beneath -3 dB it is sufficient. [23]

Centre Time (TS)

The Centre Time is a quantity for the time location of high acoustic powers. A short Centre Time corresponds to a steep increase of the energy curve. Good speech intelligibility is reached with TS<70 ms. [23]

$$TS = \frac{1}{W_{total}}\int_0^\infty t\cdot p^2(t)dt \qquad \text{[s]}$$

Clarity (C80)

What C50 is for speech is C80 for music. The Clarity C80 describes the transparency, i.e. the recognisability of consecutive tones and the possibility to differentiate between different instruments. [23]

$$C_{80} = 10\log\frac{W_{0...80}}{W_{80...\infty}} \qquad \text{[dB]}$$

Lateral energy fraction (LF)

Lateral reflexions give the desired spatiality of a room, even more than reverberation. They occur particularly in narrow concert halls because the lateral reflexions reach the listener before the reflexions from the ceiling. For concert halls, values between 25 % and 40 % are desirable. [23]

$$LF = \frac{(W_{5...80})_{lateral}}{W_{0...80}} \qquad [\%]$$

2.3 Standards

Over the years a number of recommendations for the design of (reference) listening rooms have been published by different organisations. This Section will give the reader an overview and comparison of the standards currently in use. Furthermore, it will justify the choice of the standard that is being used to design the listening room which is subject to this work.

2.3.1 Existing standards – a comparison

Currently two of the five main standards have taken root not only in research environments, but also in the business community, namely the EBU 3276[14, 15] and the ITU-R BS 1116-1 [1]. This is probably due to the fact, that these two recommendations, compared to others, like AES, IEC or N 12-A, give clear and quite strict conditions and instructions on how the room and its sound field should look like.

IEC 60268-13

The predecessor of this standard, IEC 268-13 was developed as early as 1985, thus being one of the earliest recommendations dealing with the specification of listening rooms. IEC 60268-13, in this form published 1998, is mainly a guide to provide a controlled listening environment representing a domestic listening situation. The major defects of this recommendation, however, are the regional differences of home listening environments. No guidance is provided for such differences nor is it stated which region the specifications have been defined for. [13]

Details on room dimensions, reverberation field, background noise etc. can be found in Table 2.2**.** Further, it is recommended that the room should be normally furnished (living room situation) including absorbent carpets reflecting ceilings and comfortable low back chairs that do not obstruct the sound near the listener’s head. [13]

ITU-R BS 1116-1

On the basis of the IEC 268-13 Recommendation, the ITU-R set up a standard for the assessment of small impairments in audio systems. It also contains the characteristics for a reference listening room. Though not very different from IEC 268-13, ITU-R BS 1116-1 has still some significant differences, namely [13]:

- Shorter reverberation time
- Lower noise level
- Specification for early reflected sound
- Specification for operational room response
- Lack of furnishings

"The reader should be aware that there are slight differences between the room requirements specified within ITU-R Recommendation BS 1116 and the revised edition ITU-R BS 1116-1 and certain rooms have been built according to the earlier recommendation" [13]

The ITU-R BS 1116-1 standard has by now been implemented in a number of test rooms across Europe (see Table 2.1).

	Length (m)	Width (m)	Height (m)	Floor area (m^2)	Room volume (m^3)	Room orientation
BBC R&D [7]	6.76	4.94	2.70	33.40	90.20	wide
University of Surrey	7.35	5.70	2.50	41.90	104.70	long
Nokia Research Centre	5.83	5.31	2.70	31.00	83.60	long
Helsinki University of Technology [5]	6.35	5.60	2.70	35.60	96.00	long

Table 2.1: Comparison of aspect ratios of several ITU-R BS 1116-1 conformant listening rooms [13]

EBU 3276

The European Broadcasting Union (EBU) has released two documents on the requirements of a listening room. One for two-channel sound [14] and a supplement on multichannel sound [15]. Its primary objective is to achieve a sound at the best equal to what the listener hears at home. [13]

The EBU specifications are based upon ITU-R BS 1116-1 with some additional details that can be seen in Table 2.2.

AES 20 and N-12 A

The Technical Recommendation AES 20, released by the Audio Engineering Society in 1996 has not found its way into being internationally used (not as far as is known to or has been found in literature by the author). In this respect it does not seem wise to the author to choose a standard that has not been able to prove itself on an international level.

The N-12 A, published by the Nordic Broadcasting Companies in 1992, was designed only for the testing of loudspeaker systems [4]. It definitely represented the state of the art during its time, i.e. 1970's-1990's. However, the document is not available any more [22]. Hence, this recommendation is not purposeful since the finished room will serve as an assessment environment, not only for loudspeakers, but also for speech quality, microphones etc.

For the reasons given above, both the recommendations AES 20 and N-12 are not suitable for the design of the room subject to this work and they will not be described further. For details see Table 2.2.

	IEC 60268-13	ITU-R BS 1116-1 [1]	EBU 3276 [14,15]	AES 20	N-12 A
Application	Listening tests of loudspeakers in domestic environments	Subjective assessment of small impairments	Critical assessment and selection of programme material	Listening test of studio and high-quality loudspeakers	Reference listening room for listening tests
Basis	-	Expansion of IEC 60268-13	Similar to ITU-R BS 1116-1	-	-
Floor area (m^2)	1-2 channel: 25-40 Multichannel: 30-40	1-2 channel: 20-60 Multichannel: 30-70	>40	>20	60+/- 10
Room volume (m^3)	-	-	<300	50-120	-
Room shape	-	-	-	Rectangular advice	Rectangular or trapezoidal
Aspect ration	(w/h)≤(l/h)≤(4.5(w/h -4)) l/h<3 w/h<3	(w/h)≤(l/h)≤(4.5(w/h-4)) l/h<3 w/h<3	(w/h)≤(l/h)≤(4.5(w/h -4)) l/h<3 w/h<3	h>2.1m	l:w=1.25 - 1.45 w:h=1.1 - 1.9 l:h ≤ 1.9 or ≥ 2.1
Reverberation time (s)	Tm=0.3-0.6 (1/3 Octave, 200-4000 Hz)	Tm= 0.25(V/V0)^1/3 (200-4000 Hz) V0=100 m^3	Tm= 0.25(V/V0)^1/3 (200-4000 Hz) V0=100 m^3	0.45 s (mid-range)	Tm=T0(S/S0)^1/2 (200-2500 Hz) S0=60 m^2 and T0=0.35 s
Early energy	-	10 dB attenuation of early reflections (15 ms, 1-8 kHz)	10 dB attenuation of early reflections (15 ms, 1-8 kHz)	-	Sufficient diffusion over listening area to avoid flutter echoes
Late energy	-	-	-	Suppress flutter echoes	10 dB attenuation of early reflections (10 ms, >400 Hz)
Background noise level	NR 15	NR 10, NR 15 max.	NR 10, NR 15 max.	35 dBA and 50 dBC	NR 10 or 15 dBA
Loudspeaker issues	1-2 channel and multichannel	1-2 channel and multichannel	1-2 channel and multichannel	-	Refer to Recommendation N 12-B for loudspeaker requirements (1 - 2 channel only)
Listener issues	-	-	-	-	Capacity: 6 - 10 listeners

Table 2.2: Overview of the primary differences between the various listening room standards and Recommendations [13]

2.4 ITU-R BS 1116-1

The most suitable of all standards described in Section 2.3.1 for the room to be specified, proved to be the Recommendation ITU-R BS 1116-1 [1] from the International Telecommunication Union. Not only is it suitable for the room size available (Section 2.3.1) but it also deals with the problems of room modes in small rooms adequately.

Moreover, the ITU-R recommendation contains the most stringent conditions when it comes to the sound field parameters. This standard has already been successfully realized in a number of listening rooms of similar dimensions (see Section 2.3.1).

In the following sub-Sections, the requirements for the reference loudspeakers, the reference listening room, the reference sound field conditions, the listening level and the listening arrangement as demanded by the ITU-R BS 1116-1 standard [1] are stated. In the Sections 2.4.1.1 to 2.4.1.5 the ITU-R BS 1116-1 standard is cited in extracts. The full standard can be found in Appendix B.

2.4.1.1 Reference monitor loudspeaker

Amplitude vs. frequency response

For the pre-selection of loudspeakers, the frequency response curve over the range 40 Hz-16 kHz, measured in one-third octave bands using pink noise on the main axis (directional angle 0°), should preferably be within a tolerance band of 4 dB. Frequency response curves measured at directional angles ±10° should not differ from the main axis frequency response by more than 3 dB and at directional angles ±30° (in the horizontal plane only) by more than 4 dB.

The frequency response of different loudspeakers should be matched. The difference should preferably not exceed the value of 1.0 dB in the frequency range of at least 250 Hz to 2 kHz.

Directivity index

The directivity index C, measured with one-third octave band noise, over the frequency range 500 Hz to 10 kHz, should be within the limit:

$$6 \text{ dB} \leq C \leq 12 \text{ dB}$$

The directivity index should increase smoothly with frequency.

Non-linear distortion

A constant voltage input signal producing an average sound pressure level (SPL) of 90 dB is supplied to the loudspeaker. Related to that SPL, no harmonic distortion component in the fundamental frequency range 40 Hz to 16 kHz shall exceed the following values:

$$-30 \text{ dB } (3\%) \text{ for } f < 250 \text{ Hz}$$

$$-40 \text{ dB } (1\%) \text{ for } f \geq 250 \text{ Hz}$$

Transient fidelity

The decay time measured on an oscilloscope to a level of 1/*e* (approximately 0.37) of the original level, (on the main axis only) should be:

$$t_s < 5 / f$$

where *f*: frequency.

Time delay

Time delay differences between the channels for a stereophonic or multichannel system should not exceed 100 ms.

Dynamic range

The maximum operating sound level which the loudspeaker can produce for a time period of at least 10 min without thermal or mechanical damage and without overload circuits being activated, measured with a programme simulating noise signal (according to International Electro technical Commission (IEC) Publication 268-1c), should be:

$$L_{eff\ max} > 108 \text{ dB}$$

measured by using a sound level meter set to flat response and RMS. (slow).

The equivalent acoustic noise level generated by a single reference monitor loudspeaker and associated amplifier, referenced to a distance of 1 m from the acoustical centre should be:

$$L_{noise} < 10 \text{ dBA}$$

2.4.1.2 Reference listening room

Room size (floor area)

– For monophonic or two-channel stereophonic reproduction: 20-60 m^2
– For multichannel stereophonic reproduction: 30-70 m^2

Room shape

The floor area should preferably be shaped as a rectangular or trapezium.

Room proportions

The following dimension ratios should be observed to ensure a reasonably uniform distribution of the low-frequency eigentones of the room:

$$1.1\, w / h \leq l / h \leq 4.5\, w / h - 4$$

where:

l : length; *w* : width, *h* : height.

Additionally, the conditions $l / h < 3$ and $w / h < 3$ should apply.

Reverberation time

The average value of reverberation, T_m, measured over the frequency range 200 Hz to 4 kHz should be:

$$T_m = 0.25\ (V / V_0)^{1/3}\ \text{s}$$

where: V : volume of room; V_0 : reference volume of 100 m³.

The tolerances to be applied to T_m over the frequency range 63 Hz to 8 kHz are given in Fig. 2.13.

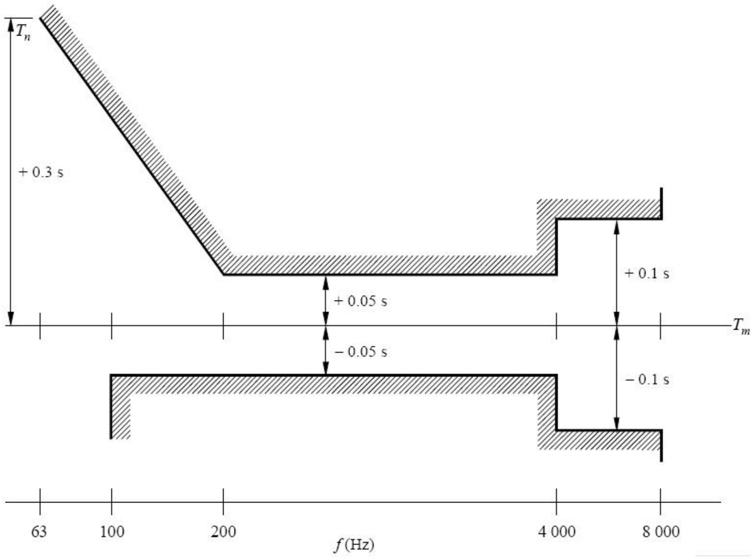


Fig. 2.13: Tolerance limits for the reverberation time relative to the average value T_m [1]

2.4.1.3 Reference sound field conditions

Frequency response of monitor Loudspeaker

The frequency response of the loudspeaker(s), measured under free field conditions, should fulfil the requirements shown in Section 2.4.1.1.

Early reflections

Early reflections caused by the boundary surfaces of the listening room, which reach the listening area during a time interval up to 15 ms after the direct sound, should be attenuated in the range 1-8 kHz by at least 10 dB relative to the direct sound.

Late energy

In addition to the specified requirements for early reflections and reverberation, it is necessary to avoid other significant anomalies in the sound field, such as flutter echoes, tonal colorations, etc.

Operational room response curve

The operational room response curves are defined as the one-third octave frequency responses of the sound pressure levels produced by each monitor loudspeaker at the reference listening position, using pink noise over the frequency range 50 Hz-16 kHz. The measured operational room response curves should fall within the tolerance limits given in Fig. 2.14.

The differences between the operational room response curves produced by each of the (stereo or multichannel) front loudspeakers at the reference listening point should not exceed the value of 2 dB within the whole frequency range.

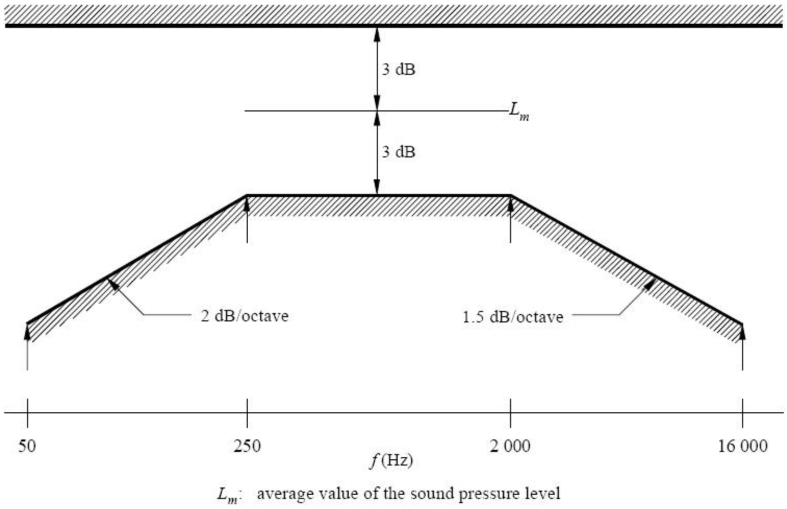


Fig. 2.14: Tolerance limits for the operational room response curve

Background noise

The continuous background noise (produced by an air conditioning system, internal equipment or other external sources), measured in the listening area at a height of 1.2 m above the floor should preferably not exceed NR 10 (see Fig. 2.15).

Under no circumstances should the background noise exceed NR 15.

The background noise should not be perceptibly impulsive, cyclical or tonal in nature.

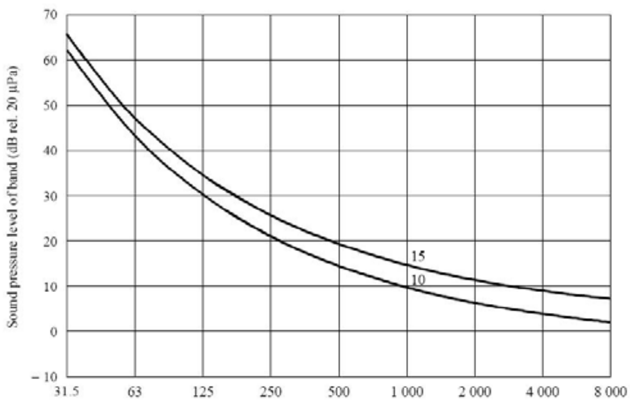


Fig. 2.15: One third octave (left) and octave (right) band background noise level limits rating curves, based on the former ISO NR curves, ISO Recommendation R1996 (1972) [1]

2.4.1.4 Listening level

Operational sound pressure level (reference listening level)

The reference listening level is defined as a preferred listening level, produced with a given measuring signal at the reference listening point. It characterizes the acoustic gain of the reproduction channel in order to ensure the same sound pressure level in different listening rooms for the same excerpt.

The level alignment of each of the loudspeakers of a listening arrangement must be carried out using pink noise. For a measuring signal with an RMS voltage equal to the “alignment signal level” (0 dBµ0s according to Recommendation ITU-R BS.645; –18 dB below the clipping level of a digital tape recording, according to [EBU, 1992]) fed in turn to the input of each reproduction channel (i.e. a power amplifier and its associated loudspeaker), the gain of the amplifier should be adjusted to give the reference sound pressure level (IEC/A-weighted, slow).

$$L_{ref} = 85 - 10 \log n \pm 0.25 \text{ dBA}$$

where n is the number of reproduction channels in the total set-up.

2.4.1.5 Listening arrangements

Height and orientation of monitor loudspeakers

The height of all the monitor loudspeakers, measured to the acoustical centre of the loudspeaker, should be about 1.2 m above floor level. This represents the ear height of a seated listener. The orientation of the loudspeakers should be such that their reference axes should pass through the reference position at a height of 1.2 m.

Distance to the wall

For free standing loudspeakers, the distance of the acoustical centre of a loudspeaker from the surrounding reflecting surfaces should be at least 1 m.

Monophonic reproduction (Fig. 2.16)

For reproduction of monophonic signals, a single loudspeaker has to be used. The minimum listening distance should be 2 m and all listening positions should be within an angle of ± 30° from the loudspeaker axis.

Two-channel stereophonic reproduction (Fig. 2.17)

<u>*Base width, B*</u>

Preferred limits are B = 2-3 m. Values of B up to 4 m may be acceptable in suitably designed rooms.

Listening distance, D

Limits of listening distance are $D = 2$ to $1.7\ B$ [m].

Listening position

The so-called reference listening point is defined by the listening angle of 60°.

The recommended listening area should not exceed the radius of 0.7 m around the reference listening point. Additional "worst case" listening positions are also shown in Fig. 2.17.

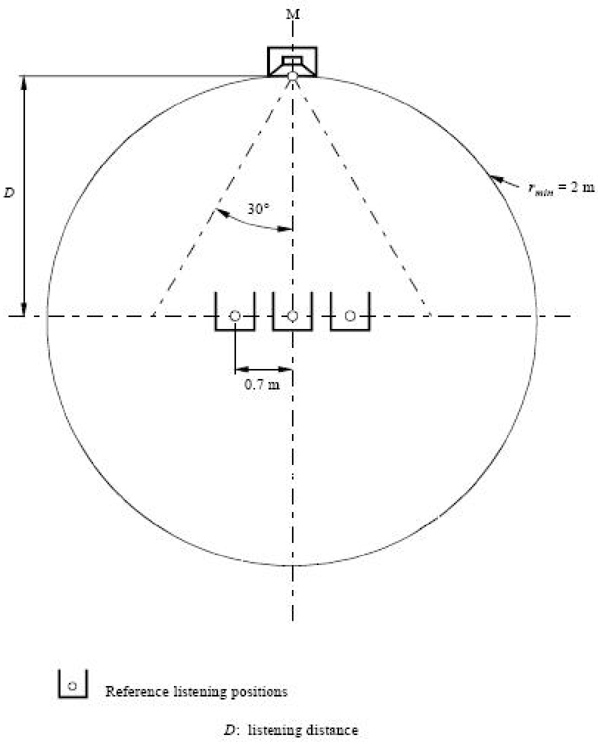


Fig. 2.16: Reference listening arrangement with loudspeaker M and permitted listening area for monophonic sound systems [1]

Multichannel stereophonic reproduction (

Fig. 2.18)

The listening arrangement should in principle correspond to the 3/2 multichannel sound layout, as specified in Recommendation ITU-R BS.775, Fig. 1 "Reference loudspeaker arrangement with loudspeakers L/C/R and LS/RS".

Base width, B

Preferred limits are $B = 2$-3 m. Values of B up to 5 m may be acceptable in suitably designed rooms.

Listening distance and base angle

The reference listening distance shall be *B* and thus the reference base angle is equal to 60°.

Listening position

The so-called reference listening point is defined by the listening angle of 60°. The recommended listening area should not exceed the radius of 0.7 m around the reference listening point. Additional "worst case" listening positions are also shown in Fig. 2.18.

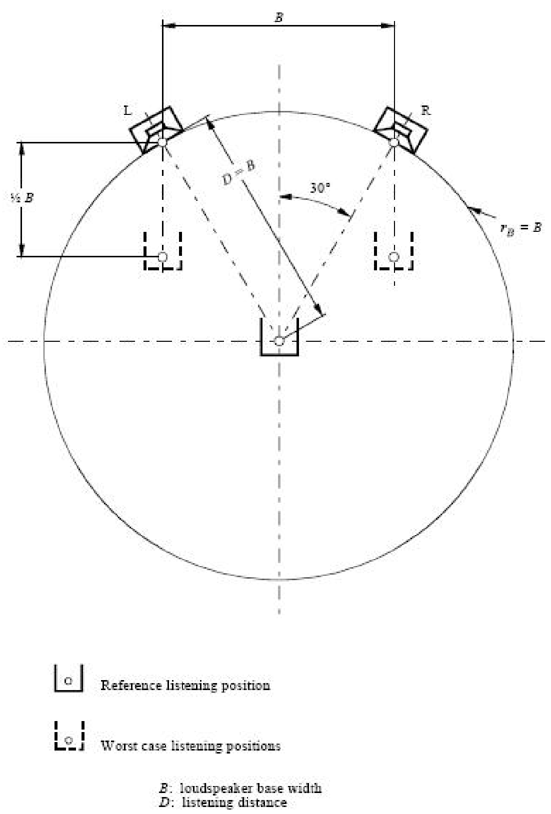


Fig. 2.17: Test listening arrangement with loudspeakers L and R for stereophonic sound systems with small impairments [1]

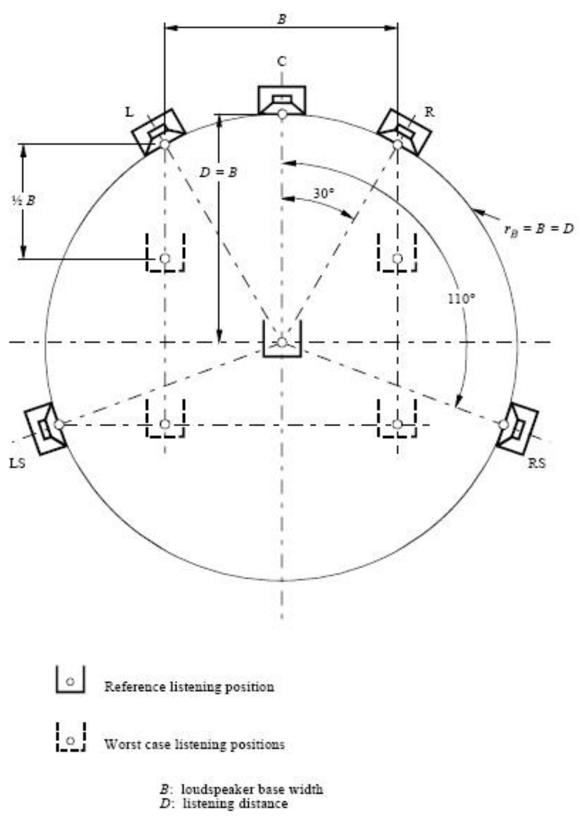


Fig. 2.18: Test listening arrangement with loudspeakers L/C/ R and LS/RS for multichannel sound systems with small impairments [1]

3 Specifications for the AAP listening room

3.1 Boundary conditions

This sub-Section will state the initial conditions of the target room including the measurement results of its sound field as well as the desired target state after the completion of the optimization process.

3.1.1 Current state

The target room itself and the means of measuring its acoustics are described here.

3.1.1.1 Room Geometry

The room to be the reference listening room has a floor area of about 30 m². The volume amounts to approximately 82 m³. Fig. 3.1 shows the floor plan of the room with its detailed admeasurements. For a 3D representation see Fig. 3.9.

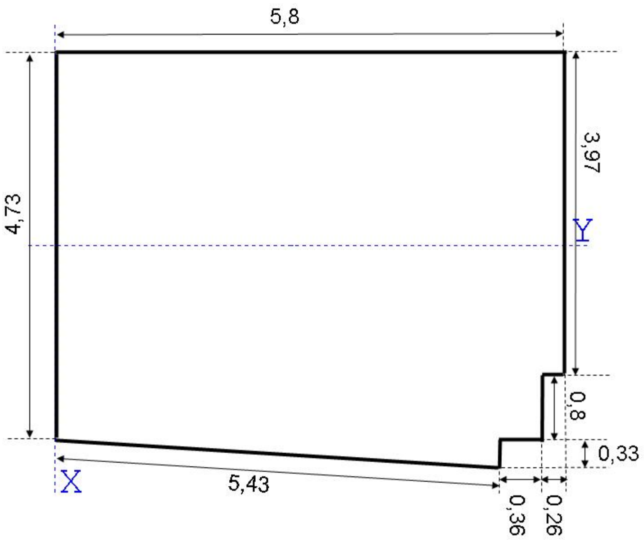


Fig. 3.1: Floor plan of the room provided by JOANNEUM RESEARCH

Below in Fig. 3.2 photos of the empty room show the initial state of the project's target room. As can be seen the room is constructed of conventional (probably brick) walls. The windows and door are standard products from the construction time of the whole building, which probably was built in the 1970s.

Fig. 3.2: Pictures of the initial, empty target room

3.1.1.2 Acoustic measurements of the empty room

The measurements of the empty target room are being accomplished by the commercially available software WinMLS. The software uses the so-called MLS method to determine the transfer function of the room, out of which other desired parameters (e.g. reverberation time) can be calculated. The principle of the method shall shortly be outlined below.

Maximum Length Sequence (MLS)

This method determines the impulse response with the aid of a reproducible and energetic signal, the MLS signal. A main advantage of the method is that it is not the excitation signal which has to be as similar to the ideal impulse but its auto-correlation function. [23]

The MLS signal is a periodic, binary, and pseudo-random signal with a period of L that is being converted into a two-valued analogue signal. The RMS value of the MLS signal is independent of the period and thus always equal to 1. The crest factor is also minimal (=1). [23]

The system under test is now excited by such an MLS signal. The system response is then measured and cross-correlated with the known excitation signal. This yields the so-called periodic impulse response (PIR). Fig. 3.3 shows the principle of such a measurement. By applying the DFT we get the complex, discrete transfer function with which we can calculate all other necessary quantities. [23]

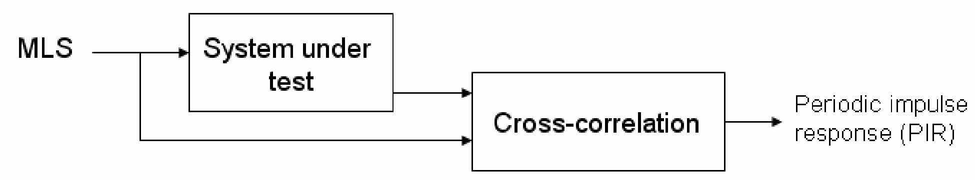


Fig. 3.3: Principle of the MLS measurement

Another advantage of the MLS method is that it is immune towards transient noise. By calculating the impulse response via the cross-correlation parts, all parts not correlating with the MLS signal, i.e. noise can be ignored.

The measurement

The original room shape, in which the measurements took place, is the one with the step in the ceiling and the windows in detail (Fig. 3.9). For the measurement of the empty target room two different source positions were chosen along with a raster of 16 measuring points distributed in the room. Fig. 3.4 shows the two sound source positions and the measuring point raster. A1 denotes the omni-directional source in both pictures.

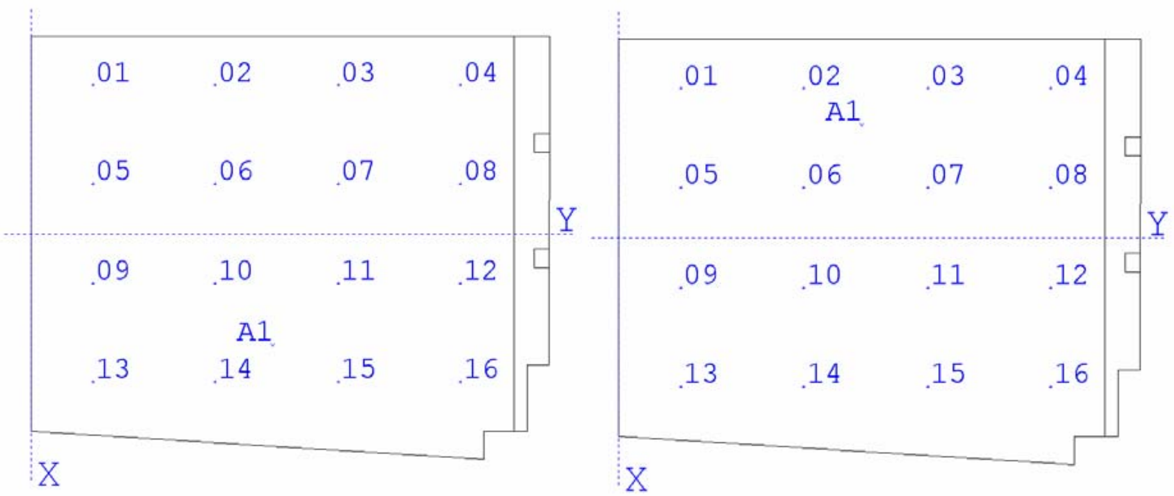


Fig. 3.4: Source Position 1 (left) and Source Position 2 (right) with the raster of 16 measuring points

The MLS signal was inducted into the room via a Norsonic 270H dodecahedron sound source whose adjusted sound level was 84.5 dB @ 1 m. This was verified with a Larson Davis 2900 digital sound level meter. The measuring device at the measuring points was a Behringer ECM 8000 omni-directional measuring microphone set at the standard listening height [1] of 1.2 m. The environmental conditions in the room were the following: temperature 26.8°C, humidity 48.9 %.

Please note: The existing background noise in the room was not measured since the installation of sound insulating windows is planned in the near future and a sound insulating door is part of the adjustments for the listening room. For this reason any measurements taken at this stage would be of no relevance to the project.

Fig. 3.5 shows the graph of the mean values of the reverberation time with the sound source at position 1. Table 3.1 gives the exact values of the average reverberation time.

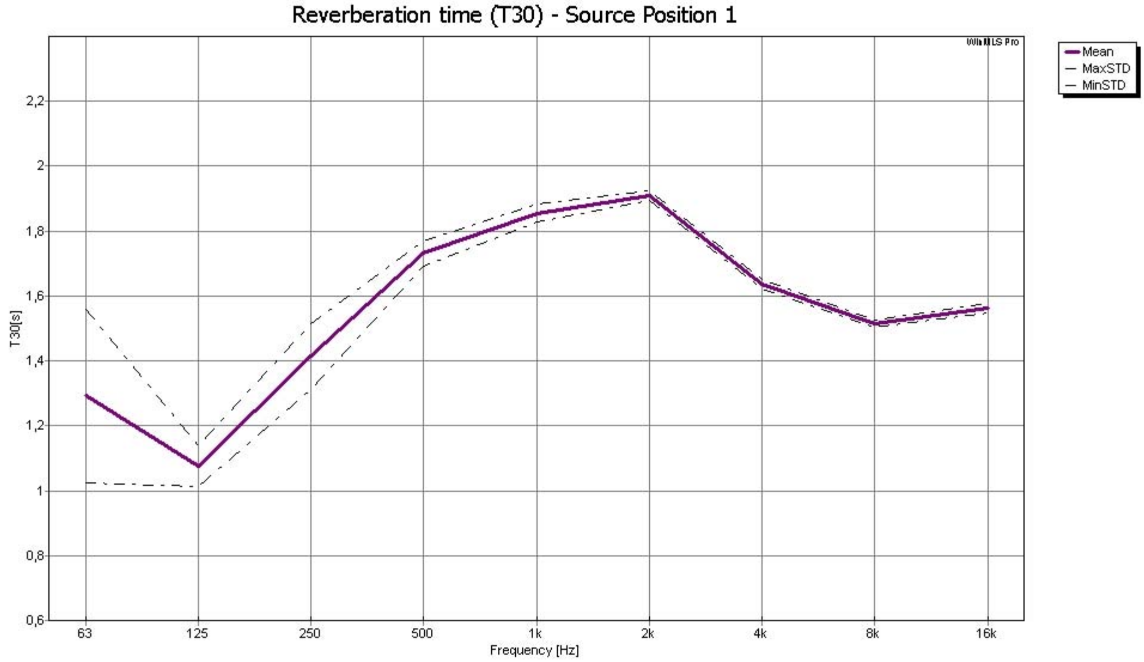


Fig. 3.5: Average reverberation time over frequency (source position 1)

[Hz]	Mean Value
63	1.292
125	1.075
250	1.414
500	1.732
1000	1.856
2000	1.910
4000	1.635
8000	1.516
16000	1.563

Table 3.1: Exact values of the average reverberation time from Fig. 3.5

As a second parameter, the clarity C80 was measured in the target room. Fig. **3.6** shows the graph of the average clarity measured. Table 3.2 gives the appropriate values.

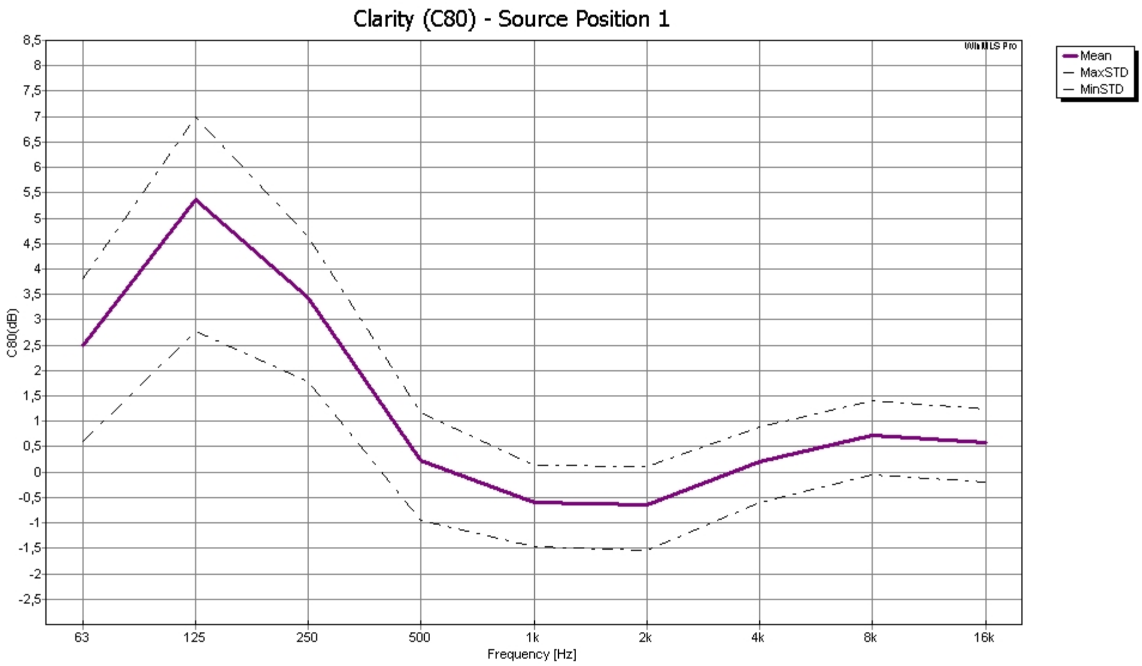


Fig. 3.6: Average clarity C80 over frequency (source position 1)

[Hz]	Mean Value
63	2.49
125	5.38
250	3.44
500	0.24
1000	-0.59
2000	-0.63
4000	0.21
8000	0.73
16000	0.58

Table 3.2: Exact values of the clarity C80 from Fig. 3.6

Fig. **3.7** shows the mean values of the reverberation time over frequency with the sound source at point 1. Table 3.3 gives the exact values of the average reverberation time.

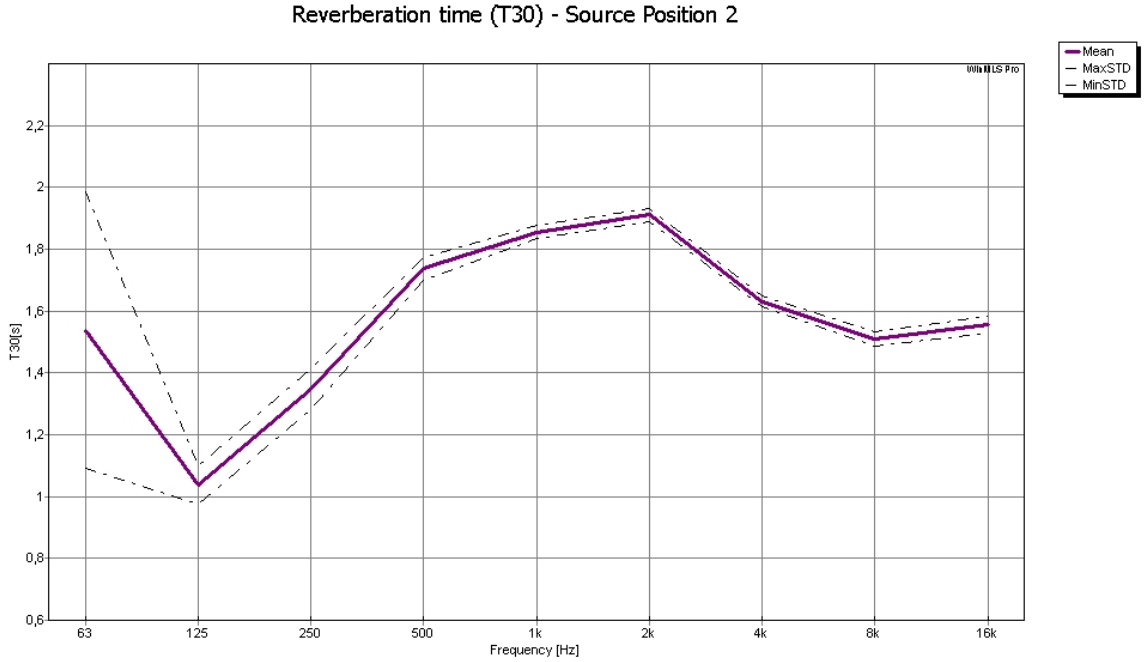


Fig. 3.7: Average reverberation time over frequency (source point 2)

[Hz]	Mean Value
63	1.537
125	1.036
250	1.347
500	1.737
1000	1.855
2000	1.911
4000	1.631
8000	1.509
16000	1.557

Table 3.3: Exact values of the average reverberation time from Fig. 3.7

Again the second parameter, the clarity C80, was measured in the target room. Fig. **3.8** shows the graph of the average clarity measured. Table 3.4 gives the appropriate values.

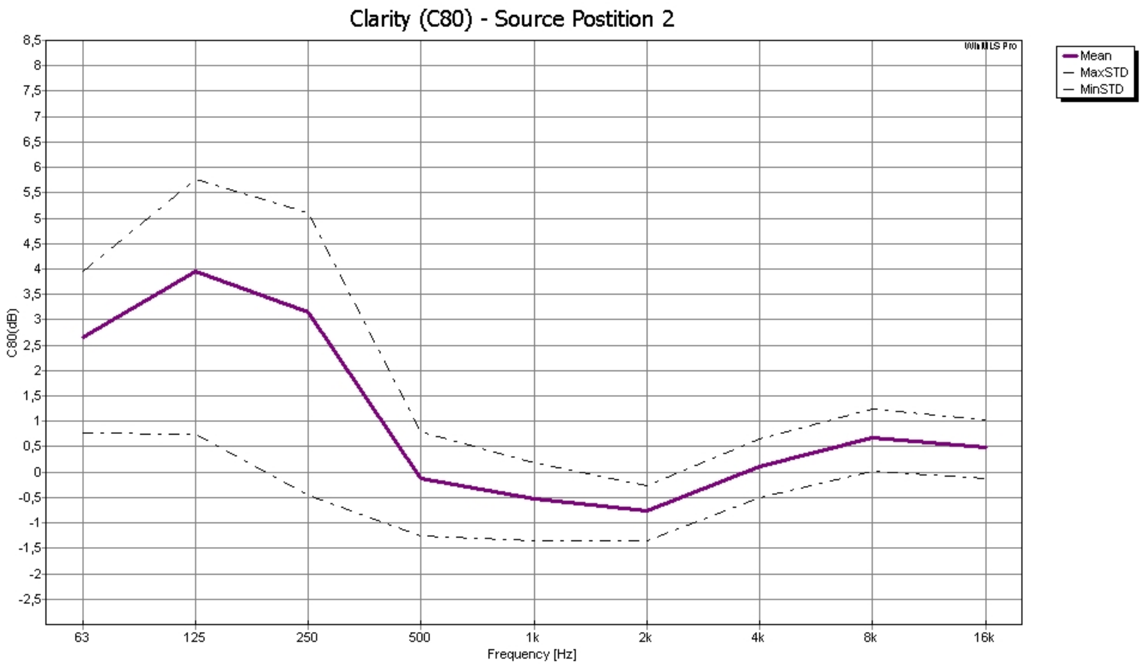


Fig. 3.8: Average clarity C80 over frequency (source point 2)

[Hz]	Mean Value
63	2.65
125	3.94
250	3.16
500	-0.11
1000	-0.52
2000	-0.77
4000	0.12
8000	0.67
16000	0.48

Table 3.4: Exact values of the average reverberation time from Fig. 3.8

Detailed results of the reverberation times with the two source positions, all raster points and their corresponding graphs can be found in Appendix A.

3.1.2 Target state

The target state of the completed room should satisfy the ITU-R BS 1116-1 standard [1] in all points.

Room size (floor area)

The floor area at hand amounts to approx. 30 m². This is sufficient for two-channel audio reproduction but critical for multichannel reproduction since at least 30 m² are required.

Room proportions

This criterion, as stated in the ITU standard, is not easy to calculate with the room shape of the target room. With the step in the ceiling, the height becomes a difficult parameter to define. To alleviate the calculation, the mean value of the two heights is taken.

The two values for the heights, *hdu*=2.32 m for the lower and *hdo*=2.97 m for the upper ceiling, are set in relation to each other according to their distribution in the room. As can be seen from Fig. 3.9, the distribution of the ceiling corresponds to about 1/3**hdu* and 2/3**hdo*. Thus the average value for the height amount to:

$$h_m = 1/3*hdu + 2/3*hdo = 2.75\ m$$

Since the room is not perfectly rectangular, additional approximations need to be made. To obtain a 30 m² floor area, the width will be assumed as *w*=5 and the length as *l*=6 m. Thus the criterion stated in Section 2.4.1.2 is as follows:

$$1.1*w / h_m \leq l / h_m \leq 4.5\ w / h_m - 4$$

$$1.1*w/2.75 \leq 6/2.75 \leq 4.5*5/2.75 – 4$$

$$\underline{\mathbf{2 \leq 2{,}182 \leq 6{,}25}}$$

It is evident that the conditions have been met with the assumptions stated above.

Additionally, the conditions $l / h < 3$ and $w / h < 3$ should apply. With l / h=2,182 and $w / h=2$ the conditions are met as well.

Reverberation time

According to CATT Acoustic®, the room volume of the target room amounts to approx. V=83 m³. V0 represents the reference volume of 100 m³. The average reverberation for the room should thus be:

$$Tm = 0.25\ (V / V0)^{1/3}\ [\mathrm{s}]$$

$$Tm = 0.25\ (83/100)^{1/3} = \underline{\mathbf{0.235\ s}}$$

Thus the tolerance limits of the reverberation time are:

$$\underline{\mathbf{0.185\ s < T_m < 0.285\ s}}$$

For early reflections, late energy, operational room response, background noise and operational sound pressure level requirements, see Section 2.4.1.3.

3.2 Simulation

3.2.1 A short introduction to CATT Acoustic®

Cited from [21]:

"CATT is an acronym for Computer Aided Theater Technique since theatre lighting and decor CAD programs were the first CATT products in 1986. Since 1988, however, CATT has concentrated on software for acoustics prediction and auralization (CATT-Acoustic) and more recently FIR reverberation tools."

"In a JASA paper ("Acoustic, acoustics", Robert T. Beyer, JASA 98(1), July 1995) the historical origins of the words acoustic and acoustics were researched. A reference from the 17th century was presented where the word "Catacoustics" was used to describe reflected sound (direct sound was called "Acoustics", and refracted sound was called "Diacoustics"). This makes the name CATT-Acoustic have some meaningful acoustical background since, indeed, reflected sound is exactly what it is about. This is of course pure coincidence since the software was named in 1988."

CATT Acoustic® is a script-based editor for room acoustic simulations. All geometric information is stored in so-called GEOMETY-files (.geo-files) where it can be modified. All points are defined through their position in a Cartesian coordinate system. The acoustically active surfaces (called PLANES) are then spanned via those points. Therefore, these points form the corner points of the PLANES and hence are called CORNERS in the programme. The surfaces can then be assigned special acoustic features, e.g. absorption, diffusion or transmission. When a complete model, i.e. a closed model with no openings, is created, a simulation can be performed on the bases of geometric features and material characteristics. Subsequently, CATT Acoustic® shall be referred to as CATT.

3.2.2 The simulation model

The CATT model of the room to be designed is shown in Fig. 3.9. It shows the original room with detailed windows and the step in the ceiling. The second variation, as seen in Fig. 3.10, shows the room with an imaginary curtain in front of the windows.

In addition, two further variations have been implemented in CATT. These show the room without the step in the ceiling. The room was modelled with the full detailed windows and with the imaginary curtain in front of them, respectively. These two variations were implemented to investigate whether the step in the ceiling incurs any major defects or perhaps even yields advantages in terms of room acoustics. Fig. 3.11 shows the variation with and Fig. 3.12 the one without the windows.

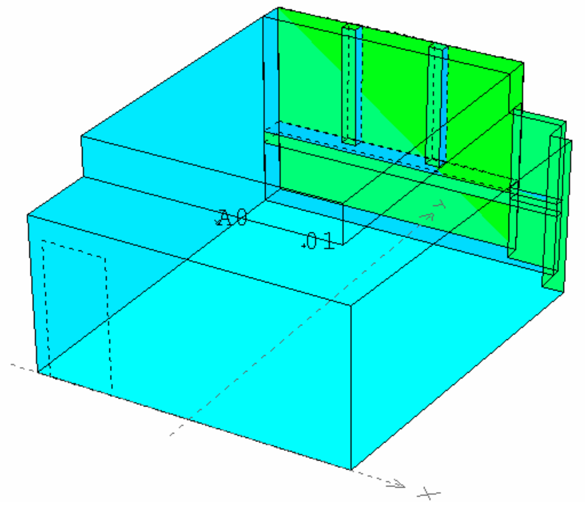


Fig. 3.9: CATT room model of the target room with windows in detail

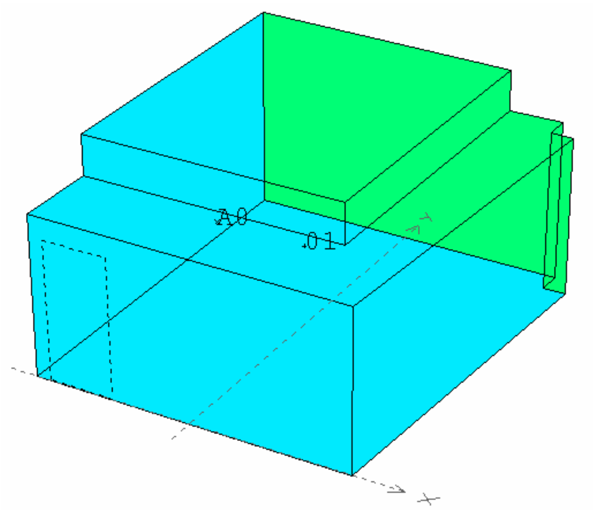


Fig. 3.10: CATT room model with a 'curtain' in front of the windows

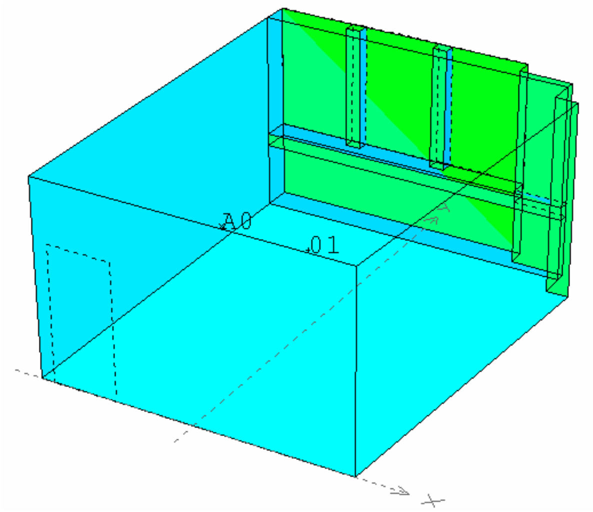


Fig. 3.11: CATT room model of the room without the step in the ceiling but with windows in detail

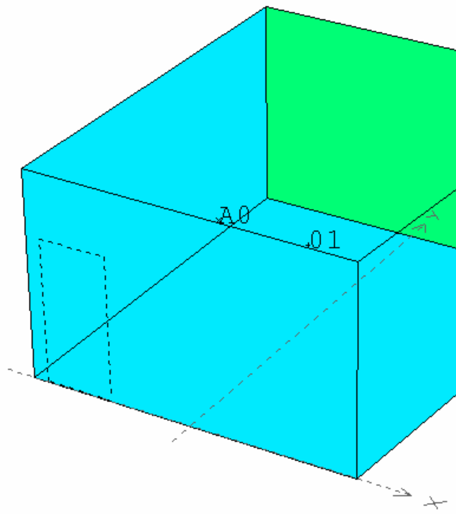


Fig. 3.12: CATT room model of the room without the step in the ceiling and with a 'curtain' in front of the windows

Model structure

The model is organized in a hierarchic pyramid structure. There is a master-geometry-file, in this project called 'MASTER_BOTH.GEO', in which all globally important data and variables, e.g. absorption materials and CORNERS and PLANES equal to all sub-files, are contained.

The simulation of all four iterations of the room is thus carried out in one setting (called 'Master_both_multi_src.PRD'). Through the INCLUDE command, sub-files are loaded in addition to the master-file. For this task, four such sub-files have been created to choose from. Fig. 3.13 shows a flowchart of the sub-files hierarchy of the simulation. By inserting the IF … THEN condition into the files, different queries can be implemented. Two queries have been implemented in the model at hand. First, the type of room is queried (see Fig. 3.14 a). ROOM=1 stands for the room with the step in the ceiling, ROOM=2 for the room without it. Then the type of window setting is asked for (Fig. 3.14 b). WINDOWS=1 represents the full detailed window side, WINDOWS=2 stands for the completion of the room by a curtain.

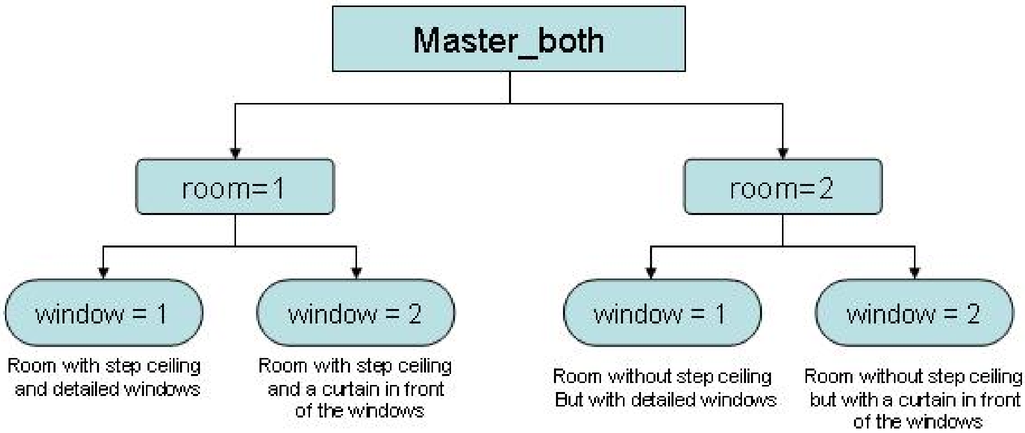


Fig. 3.13: The flowchart of the simulation query

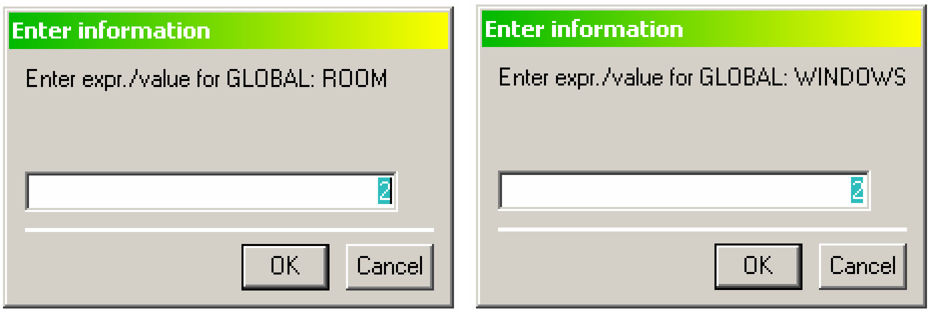


Fig. 3.14: First the simulation asks for the type of room (left), then for the window variation (right)

The applied absorbers and the room changes necessary were stored in another .GEO file called Absorber_Room1.GEO and Absorber_Room2.GEO, respectively.

3.2.3 Calibration of the model

The calibration of the model is the first, very important step towards a meaningful optimization. The values obtained during the measurement of the empty target room (Section 3.1.1.2) are entered into the simulation and approximated by altering different parameters. When this step is finished, the simulation of the empty room should yield more or less the same result as the measurement of the actual room.

For reasons of a more advantageous reverberation time, source position 1 has been chosen for the calibration. It shows slightly better reverberation behaviour in the low frequencies around 63 Hz (see Fig. 3.5 and Fig. 3.7).

3.2.3.1 Model with step in the ceiling

The clarity C80 was to be calibrated by altering the diffusivity of the simulation until the simulation would be satisfyingly consistent with the measurement values of the empty target room. The diffusivity set for each of the octave bands can be seen in the row ‘Diffs’ in Table 3.6. However, the measurement values exceed the simulated values, especially in lower frequency ranges of 125 and 250 Hz. The simulation is not capable of producing such high or low values for the clarity that the measurements suggested. The high values of the measurements in the 125 and 250 Hz octave bands can be observed throughout the measurement point results in those octave bands. The calibration has been performed in the best possible way, given the measurement values. For a comparison of the according values see Table 3.5 and the graph in Fig. 3.15.

[Hz]	Measurement	Simulation
125	5.38	3.2
250	3.44	1.4
500	0.24	0.1
1000	-0.59	-0.6
2000	-0.63	-0.5

4000	0.21	0.7

Table 3.5: Comparison of the measured and simulated clarity C80 values

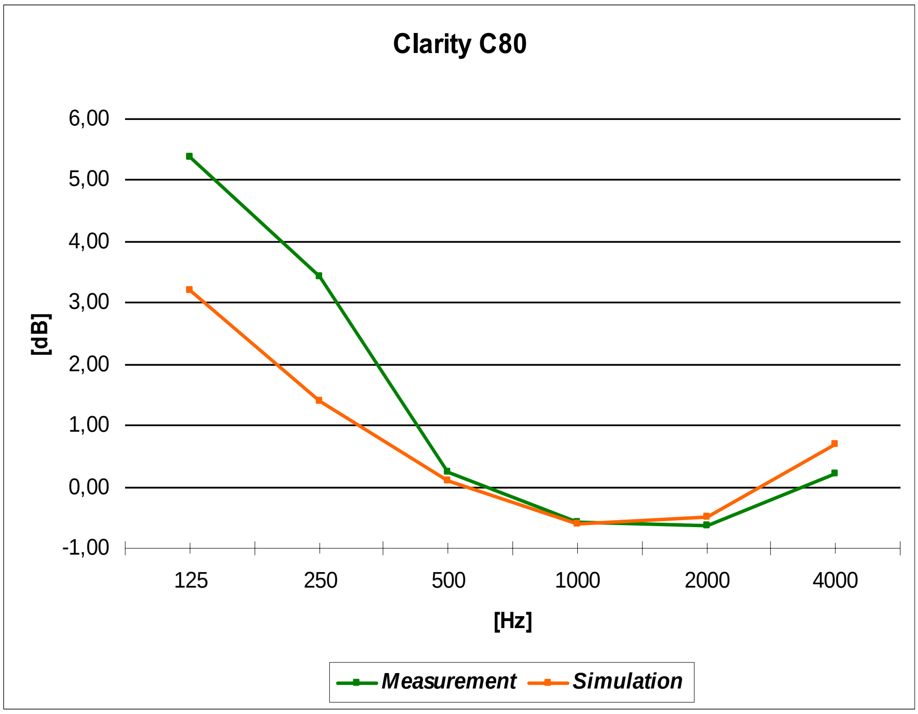


Fig. 3.15: Results of the calibration of the simulation with the measured through the clarity C80

To achieve the calibration in reverberation time, the measured reverberation time from Section 3.1.1.2 was entered into CATT as a reference value. The absorption coefficients of the walls and floor were then adjusted until the simulated and the measured values were sufficiently consistent with each other.

Since WinMLS calculated the T30 reverberation time from the measurement of the empty room, we compared it to the simulated T30 given by CATT. As can be seen in Table 3.6 and Fig. 3.16, the measured and simulated reverberation time values are very consistent with each other. The differences of maximal 0.01 s can be neglected.

	125	250	500	1k	2k	4k	
EyrT	1,05	1,38	1,67	1,88	1,82	1,51	s
EyrTg	1,00	1,30	1,61	1,80	1,80	1,50	s
SabT	1,02	1,31	1,61	1,80	1,79	1,49	s
T-15	1,09	1,41	1,70	1,89	1,89	1,57	s
T-30	1,11	1,41	1,70	1,89	1,90	1,59	s
Tref	1,10	1,40	1,70	1,90	1,90	1,60	s
AbsC	9,25	7,11	5,78	4,97	4,87	5,16	%
AbsCg	9,74	7,50	5,96	5,18	4,94	5,20	%
MFP	2,58	2,58	2,58	2,58	2,58	2,58	m
Diffs	3,01	8,03	14,04	30,00	10,00	3,99	%

Table 3.6: All reverberation times calculated by CATT; T_{ref} equals the T30 measured in the target room

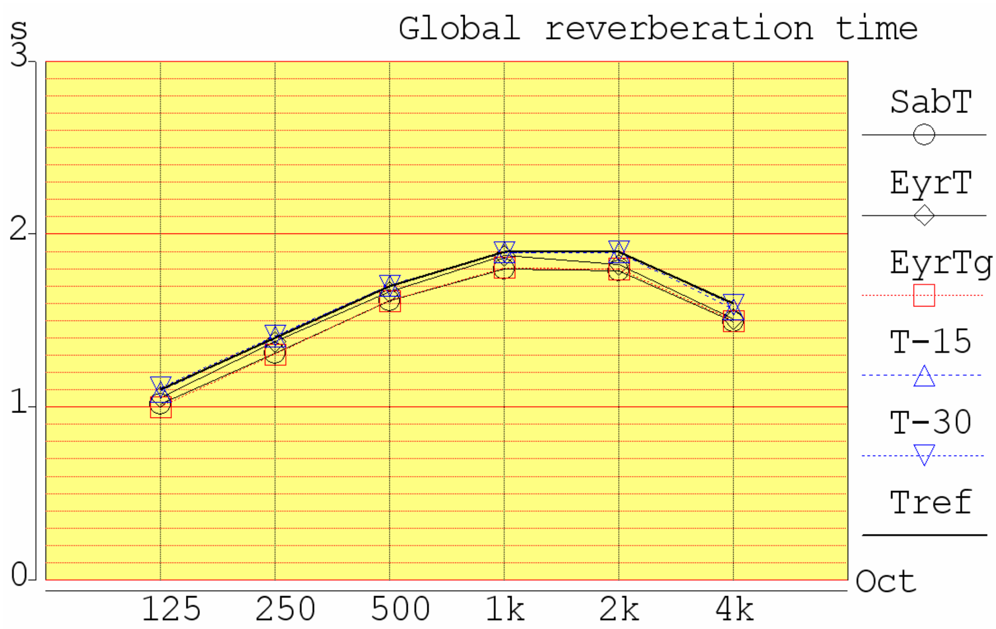


Fig. 3.16: All reverberation times calculated by CATT; T_{ref} equals the T30 measured in the target room

3.2.3.2 Model without step in the ceiling

As an additional step of the calibration, the second variation of the room, i.e. the one without the step in the ceiling, was simulated with the calibration shown in Section 3.2.3. This measure will show if the step in the ceiling incurs any additional acoustical defects or if it possibly affects the room acoustics in a positive way. Based on the results presented below, a recommendation alone cannot be given concerning the optimal room shape since the results from the table below cannot really be compared with each other.

[Hz]	Measurement	Room 2 without step ceiling	Room 1 with step ceiling
125	5.38	2.8	3.2
250	3.44	1.1	1.4
500	0.24	-0.2	0.1
1000	-0.59	-0.8	-0.6
2000	-0.63	-0.7	-0.5
4000	0.21	0.5	0.7

Table 3.7: Comparison of the clarity C80 simulated for both variations of the room

Table 3.7 gives the comparison of the calculated clarities of both room shape variations while Fig. 3.17 shows a graph of the results. The clarity parameter does change a lot for the room without the step in the ceiling but this could easily be improved by applying some acoustic architectural measures to the room. As can be seen from Fig. 3.18, the reverberation time does not change significantly. Of course it is a little higher than that from the original room, but this can be explained with the larger volume of this room variation.

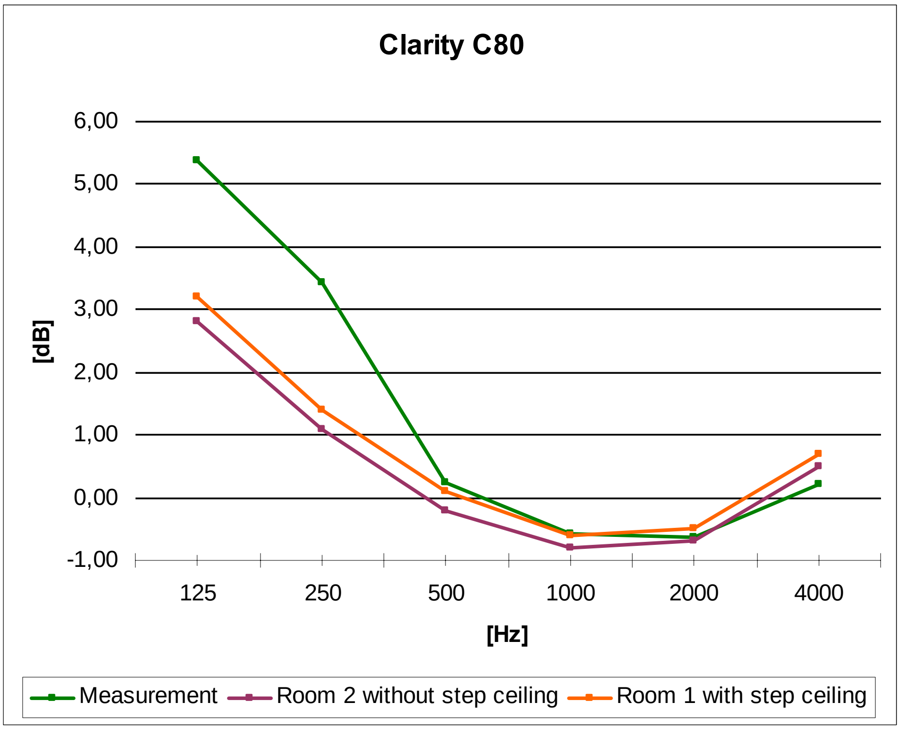


Fig. 3.17: Clarity C80 measurement compared to the simulation results of the room with and without step ceiling

	125	250	500	1k	2k	4k	
EyrT	1,11	1,44	1,75	1,96	1,92	1,57	s
EyrTg	1,11	1,44	1,76	1,96	1,92	1,57	s
SabT	1,13	1,46	1,76	1,96	1,92	1,57	s
T-15	1,14	1,47	1,79	1,98	1,98	1,63	s
T-30	1,16	1,47	1,79	1,98	1,99	1,65	s
Tref	1,10	1,40	1,70	1,90	1,90	1,60	s
AbsC	9,28	7,14	5,78	5,00	4,85	5,16	%
AbsCg	9,29	7,15	5,78	5,00	4,83	5,15	%
MFP	2,72	2,72	2,72	2,72	2,72	2,72	m
Diffs	3,02	8,02	14,00	29,99	9,98	4,00	%

Fig. 3.18: All reverberation times calculated by CATT for the room without the step in the ceiling; T_{ref} equals the T30 measured in the target room

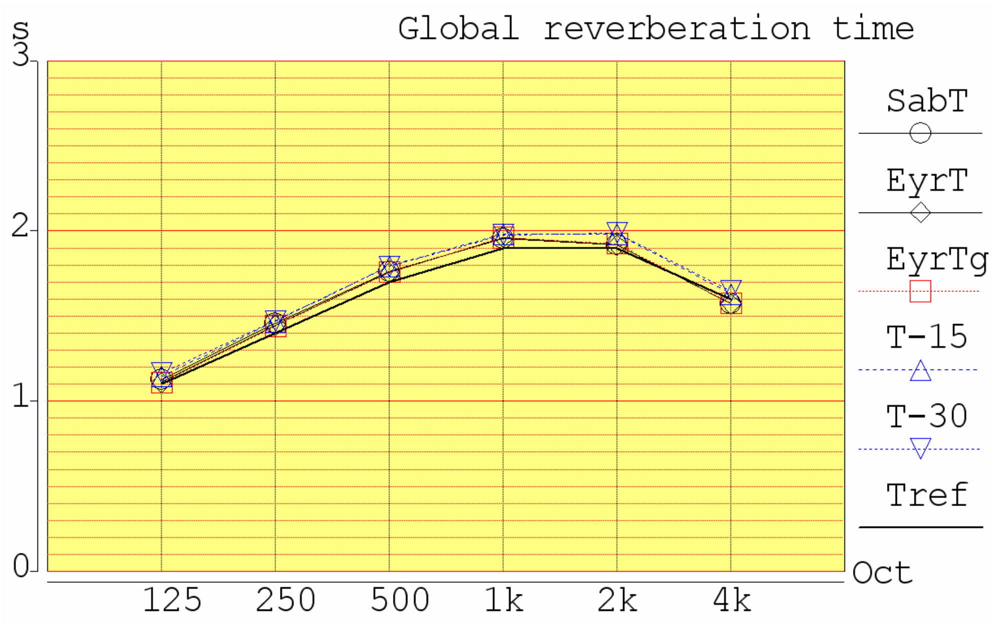


Fig. 3.19: The reverberation times calculated by CATT for the room without the step in the ceiling; T_{ref} equals the T30 measured in the target room

3.3 Recommendations for the optimization of both room variations

The optimization of the two room variations was achieved by ‘equipping’ the simulated room with acoustic material and, at the same time, considering the effects e.g. the tables of the listener and the supervisor, would have on the acoustics of the rooms. Even though the ITU standard basically specifies the sound field only through the reverberation time and the early reflections (see Sections 2.4.1.2 and 2.4.1.3), the attenuation of the two room variations in order to obtain the target average reverberation time of 0.235 s still proved to be quite a challenge. By inserting broad-band and low frequency absorbers into the simulated rooms, the acoustics was gradually approximated towards the required target conditions. A different solution for each of the two room variations, with and without the step in the ceiling, has been found.

3.3.1 Room 1 (with step in the ceiling)

3.3.1.1 Simulation results

After adjusting several different acoustic materials, such as broadband absorbers, acoustic curtains and ceilings (see Section 3.3.1.2), the results given by the simulation were finally considered to be good enough. The difficulty in adjusting the room’s acoustics lay mainly with the problem of the frequency band at 500 Hz where the limits can hardly be met. On top of that, the acoustic ceilings used here tend to have greater absorption values at 500 Hz, which makes it even more difficult to ensure the reverberation time values to be within the limits provided by the standards chosen. The only value slightly out of the limits, produced by source A4 at the problematic 500 Hz band, is of no relevance since the deviation of the lower limit amounts to only 0.005 s.

The tables for both listener and supervisor did not prove to be such a problem as one would have assumed. They changed the reverberation times of the higher frequencies (>500 Hz) only slightly. Those were simply removed through applying more of the same or other acoustic material. The values for the frequency bands at 2 kHz and 4 kHz may seem to be a little high, however they are well within the given limits, as can be seen in Fig. 3.20.

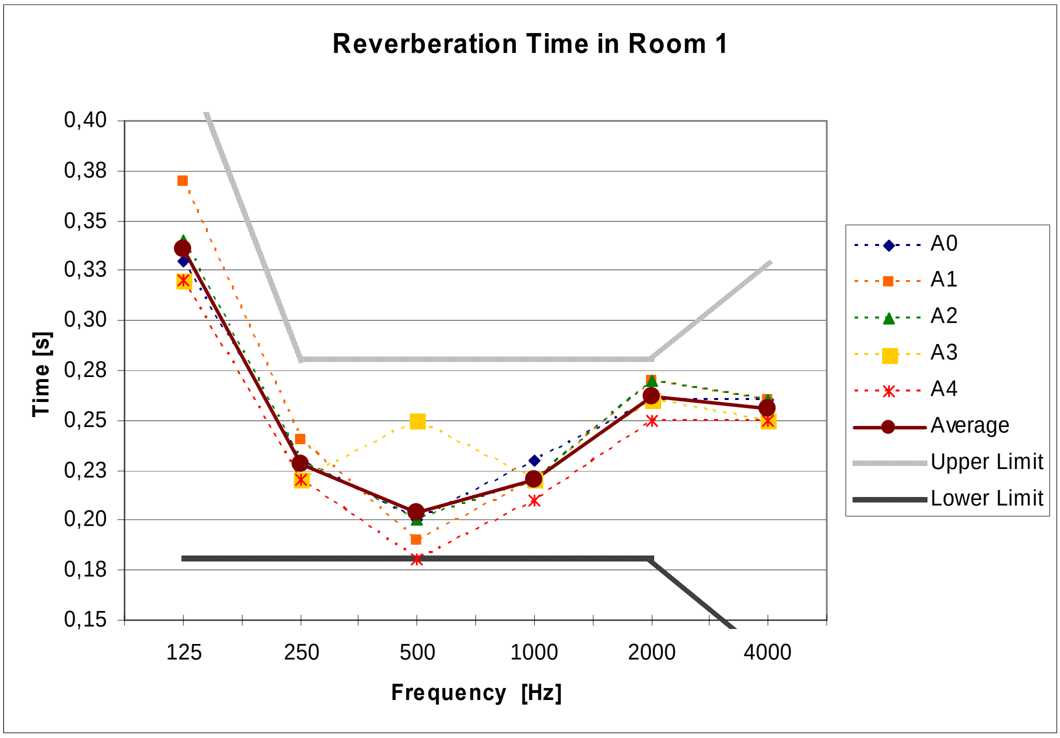


Fig. 3.20: The reverberation time simulated in Room 1 with step ceiling, A0 –A4 stand for the sources of the multisource arrangement

Table 3.8 shows the results of the reverberation time T30 as taken from the simulation. The bold values in the last line stand for the average values of all reverberation times produced by each of the five sources A0 to A4.

	125	**250**	**500**	**1k**	**2k**	**4k**
A0	0,33	0,23	0,2	0,23	0,26	0,26
A1	0,37	0,24	0,19	0,22	0,27	0,26
A2	0,34	0,23	0,2	0,22	0,27	0,26
A3	0,32	0,22	0,25	0,22	0,26	0,25
A4	0,32	0,22	0,18	0,21	0,25	0,25
	0,34	**0,23**	**0,20**	**0,22**	**0,26**	**0,26**

Table 3.8: Simulated T30 reverberation time results of Room 1 with step ceiling, A0 –A4 stand for the sources of the multisource arrangement

Where reverberation time results fairly meet the conditions stated in [1] the results of the simulated echograms produced by each of the five speakers mostly fail to be within given limits. As can be seen from Fig. 3.21 to Fig. 3.25 there are some outliers, i.e. reflections that are attenuated less than 10 dB compared to the direct sound, within the first 15 ms after the direct sound.

The main problems causing the unwanted early reflections are the ceiling (the higher one, not the lower) and the appropriate walls beside or behind the speakers. This is probably due to the too short distance between walls and speakers which ideally should be more than 1 m but can not be reached because of the room proportions. Another problem zone adds when considering the rear speakers. Here, the floor also causes some irritating early reflections, especially at the area where the carpet lies. Fig. 3.21 to Fig. 3.25 show the early echograms produced by each of the five speakers. The black ring indicates the level of the direct sound which reaches the listener 6 ms (as can be seen from the lower time axis) after being released by the speaker.

The problem occurs mainly for frequencies above 500 Hz.

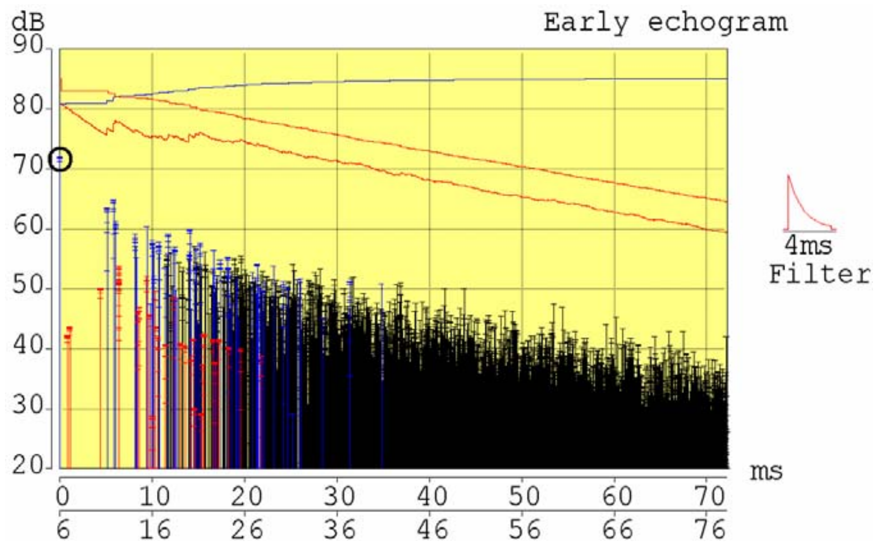


Fig. 3.21: Echogram of the Room with the step in the ceiling produced by speaker A0

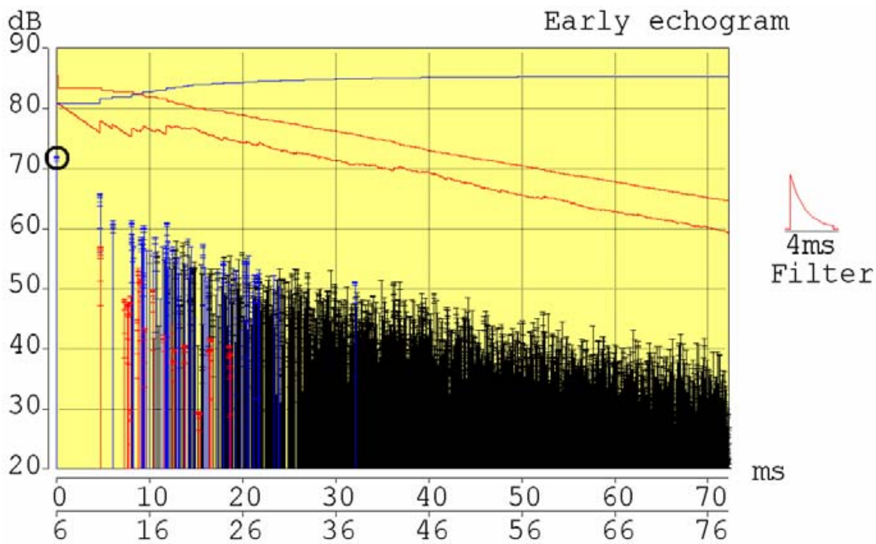


Fig. 3.22: Echogram of the Room with the step in the ceiling produced by speaker A1

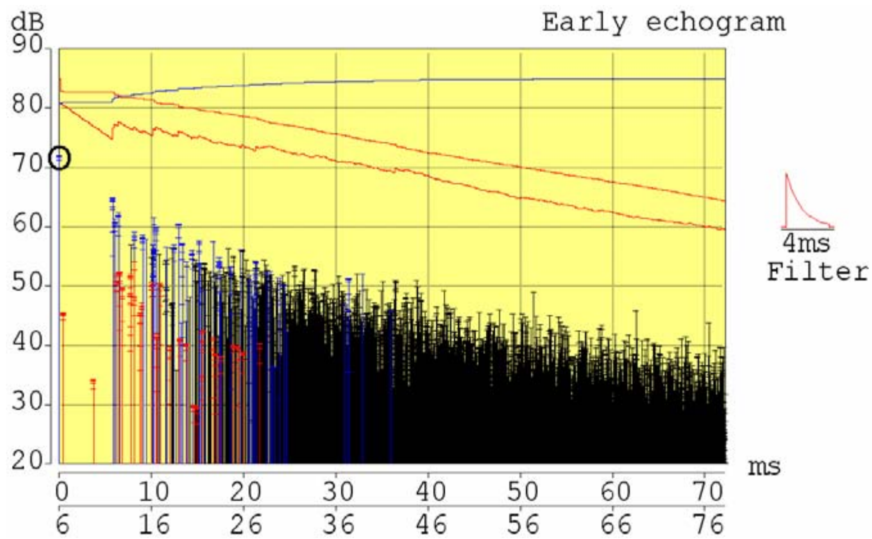


Fig. 3.23: Echogram of the Room with the step in the ceiling produced by speaker A2

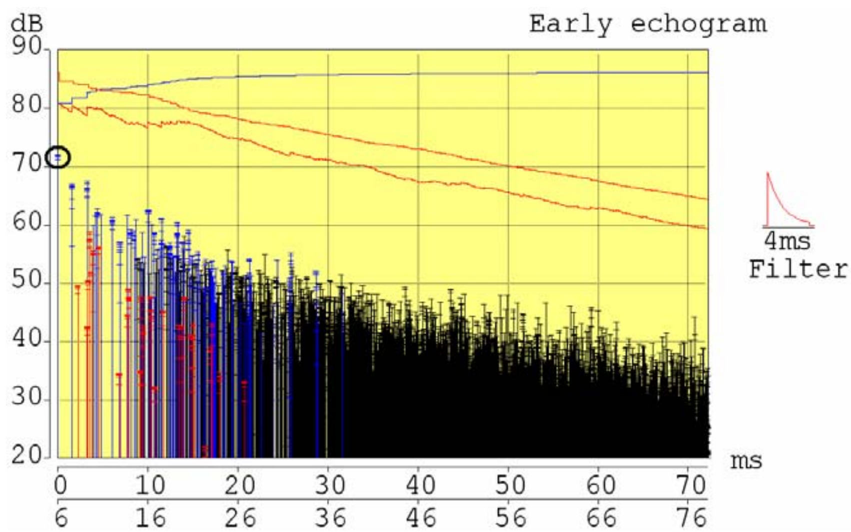


Fig. 3.24: Echogram of the Room with the step in the ceiling produced by speaker A3

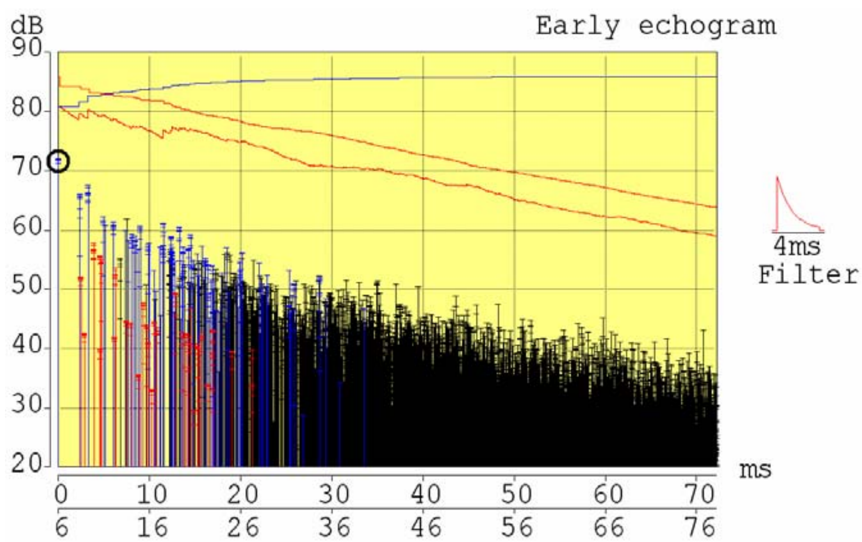


Fig. 3.25: Echogram of the Room with the step in the ceiling produced by speaker A4

3.3.1.2 Acoustic material

To master the initial acoustic situation in the target room, with the step in the ceiling, many different acoustic materials were utilized.

Broadband and Low frequency absorber

Adequate absorbers for the walls were found at 'Trikustik' (www.trikustik.at), an Austrian company. The absorption coefficients of the absorber with the appellation 'R32D8' are stated in Table 3.9.

	125	250	500	1k	2k	4k
α	0.5	0.62.	0.6	0.5	0.3	0.22

Table 3.9: Absorption coefficients of the Trikustik broad-band absorber

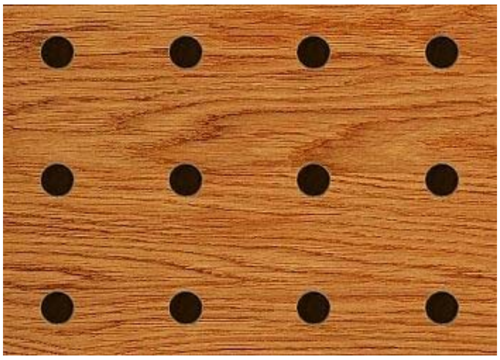


Fig. 3.26: Example picture of the perforation of the absorber R32D8 in use (www.trikustik.at)

The type of low frequency absorber that was found suitable for the room acoustics was proposed by Thorsten Rhode. This very same low frequency absorber is currently used at the MUMUTH project, the new performance hall of the University of Arts in Graz, as well as in the broadband absorber described in Section 3.3.2.2. For more details and information on the acquisition of those absorbers please contact Mr. Rhode.

	125	250	500	1k	2k	4k
α	0.91	0.77	0.45	0.25	0.14	0.14

Table 3.10: Absorption coefficients of the low frequency absorber

Acoustic curtain

The acoustic curtain used to cover the windows of the listening room is distributed by 'mbakusik', a German company (www.mbakustik.de). Table 3.11 shows the absorption coefficients of the velvet curtain AV12 with a smooth surface, Fig. 3.27 is a photo of it.

	125	250	500	1k	2k	4k
α	0.03	0.3	0.75	0.76	0.76	0.78

Table 3.11: Absorption coefficients of the acoustic curtain

Fig. 3.27: Example picture of an acoustic curtain by www.mbakustik.de

Acoustic ceiling

To deal with reflection from the ceiling, a ceiling system by KNAUF GmbH (www.knauf.at) was found suitable. The absorption coefficients of the system Tectopanel 'Globe G1' can be found in Table 3.12. Fig. 3.28 shows a tile of this ceiling system.

	125	250	500	1k	2k	4k
α	0.70	0.65	0.65	0.60	0.65	0.65

Table 3.12: Absorption coefficients of the acoustic ceiling 'Globe G1'

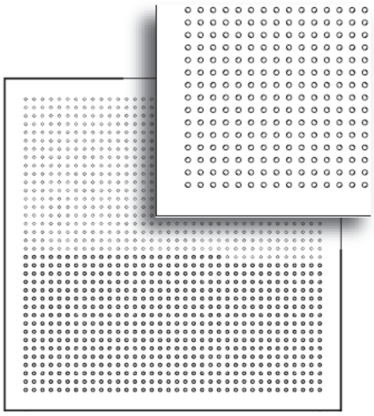


Fig. 3.28: Example picture of an acoustic ceiling tile of the type Globe G1 by KNAUF GmbH (www.knauf.at)

3.3.1.3 Placement of the absorbers

To achieve the required reverberation time, the absorbers described above have to be put in place in the following way. Fig. 3.29 shows a 3D view of Room 1 with all the acoustic material and furniture. Below a legend for the subsequent Figures can be found.

Yellow	Broadband absorbers by Trikustik
Blue windows	Rectangles are the low frequency absorbers. The curtain in front of the
Orange	Curtain in front of the windows
Red	Carpet
Turquoise	Floor
Lilac	Tables for listener and supervisor, respectively. They will be described in detail in Section 3.4.2.

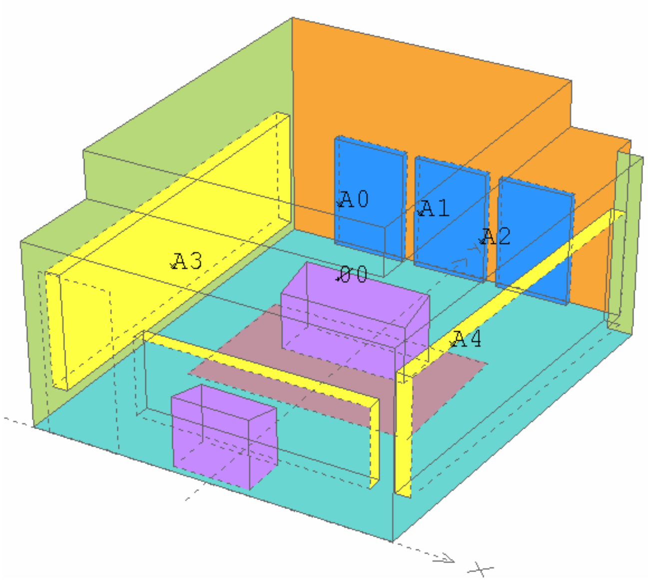


Fig. 3.29: 3D view of the fully equipped listening room

The exact positioning of the absorbers in the room will be described through the sketches below.

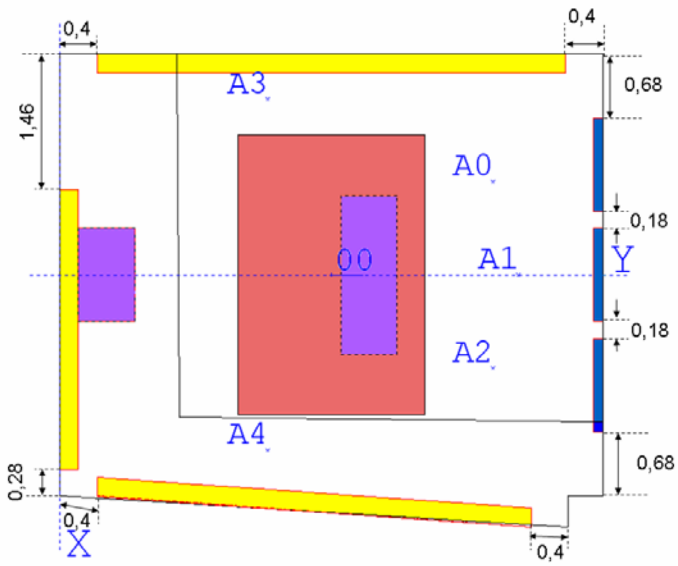


Fig. 3.30: Floor plan of the listening room with all absorbers

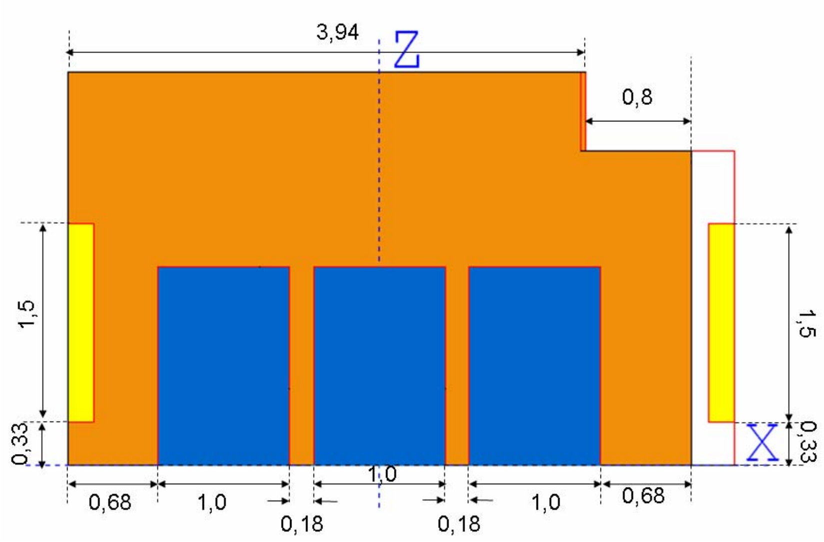


Fig. 3.31: Window perspective of the listening room with all absorbers

Please note: The acoustic curtain in Room 1 has to be divided because of the difference in the ceiling height caused by the step. To compensatethis, two curtains with different width and height have to be applied. The dimensions of the acoustic curtain for Room 1 must be as follows:

0.8 m * 2.38 m and 3.94 m * 2.98 m

In the field ‘drapery’ ‘1’ has to be selected in order to obtain a smooth curtain surface, when ordering the curtain at www.mbakustik.de.

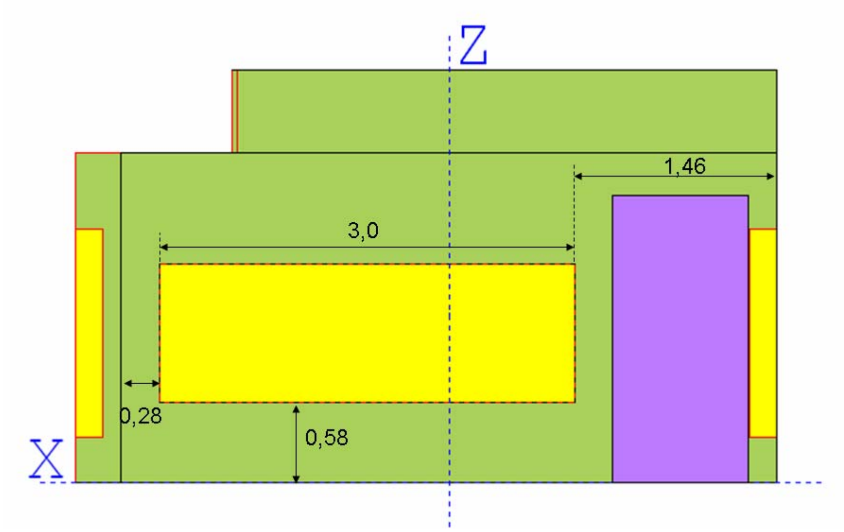


Fig. 3.32: Door perspective of the listening room with all absorbers visible from this view

3.3.2 Room 2 (without step in the ceiling)

3.3.2.1 Simulation results

The results presented below in Table 3.13 were achieved the same way as the results from Section 3.3.1.1. The only difference between the optimization of Room 1 and 2 is that the initial acoustics of Room 2 required different, speaking of broad band and ceiling, absorbers to obtain the required reverberation times (see Section 3.3.2.2). Again the problem lies with the low frequencies where the lower limits for the 500 Hz frequency band can hardly be met while the upper limit for the 250 Hz band is nearly reached. An average value of 0.19 s at 500 Hz, however, is still acceptable. Although the reverberation time value produced by source A0 at 250 Hz lies above the recommended limit, the average value meets the requirements stated in Section 3.1.2 and thus this single value is of no relevance. The same applies for the value produced by source A4 at 500 Hz. Since the value is only 0.005 s below the limit, this is of no relevance.

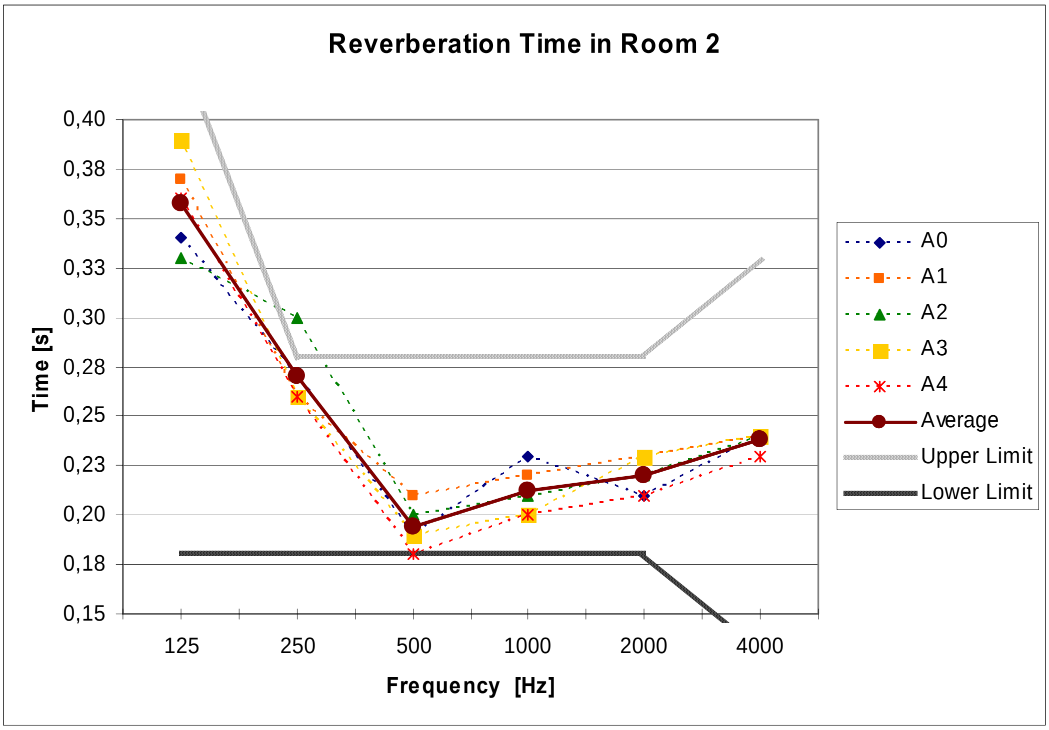


Fig. 3.33: The simulated reverberation time in Room 2 without the step ceiling

	125	250	500	1k	2k	4k
A0	0,34	0,27	0,19	0,23	0,21	0,24
A1	0,37	0,26	0,21	0,22	0,23	0,24
A2	0,33	0,30	0,20	0,21	0,22	0,24
A3	0,39	0,26	0,19	0,20	0,23	0,24
A4	0,36	0,26	0,18	0,20	0,21	0,23
	0,36	**0,27**	**0,19**	**0,21**	**0,22**	**0,24**

Table 3.13: Simulated T30 reverberation time results of Room 2 without the step ceiling

Where reverberation time results fairly meet the conditions stated in [1] as well, the results of the simulated echograms produced by each of the five speakers do not improve compared to the first room variation in Section 3.3.1.1. As can be seen from Fig. 3.34 to Fig. 3.38 there are some outliers, i.e. reflections that are attenuated less than 10 dB compared to the direct sound, within the first 15 ms after the direct sound.

As with the room with step in the ceiling similar problems with the attenuation of early reflections occur in this room variation. Like before, the main culprits are the ceiling and the walls closest to the speakers. Looking at the rear speakers the floor adds as a disturbing reflecting surface but, interestingly, the walls do not seem to influence the early reflections. The black ring again indicates the level of the direct sound which reaches the listener 6 ms (as can be seen from the lower time axis) after being released by the speaker.

Again the problem occurs mainly for frequencies above 500 Hz.

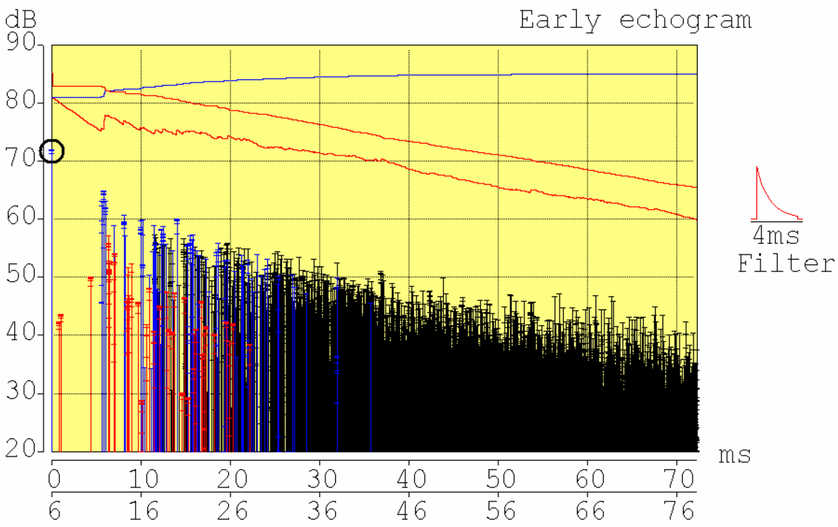


Fig. 3.34: Echogram of the Room without the step in the ceiling produced by speaker A0

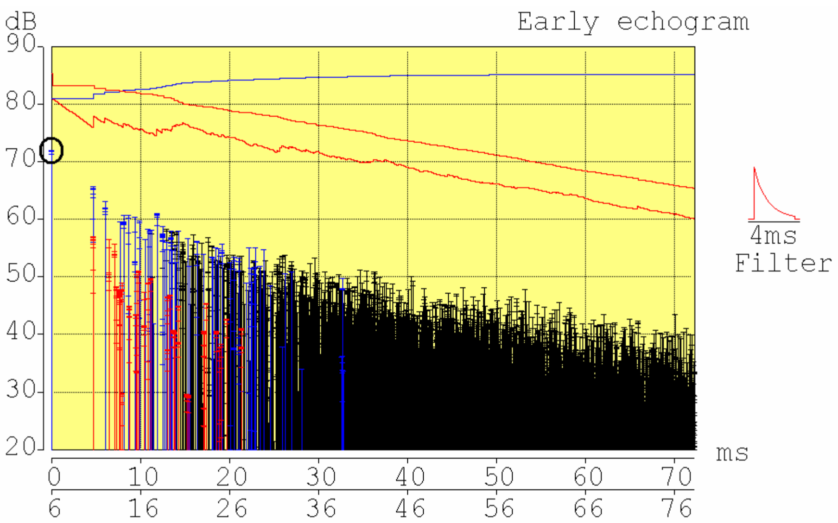


Fig. 3.35: Echogram of the Room without the step in the ceiling produced by speaker A1

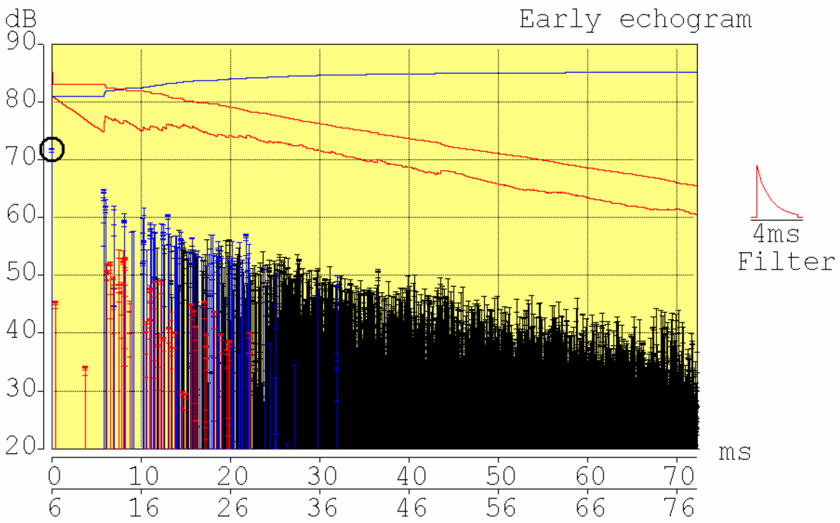


Fig. 3.36: Echogram of the Room without the step in the ceiling produced by speaker A2

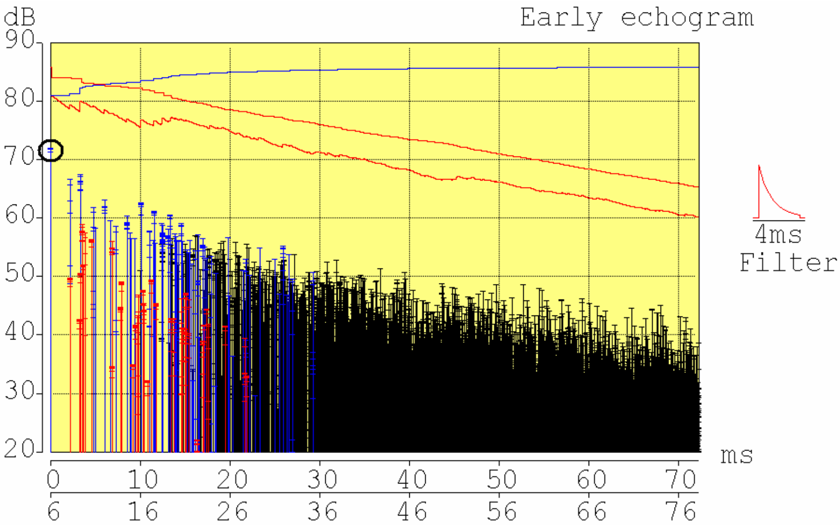


Fig. 3.37: Echogram of the Room without the step in the ceiling produced by speaker A3

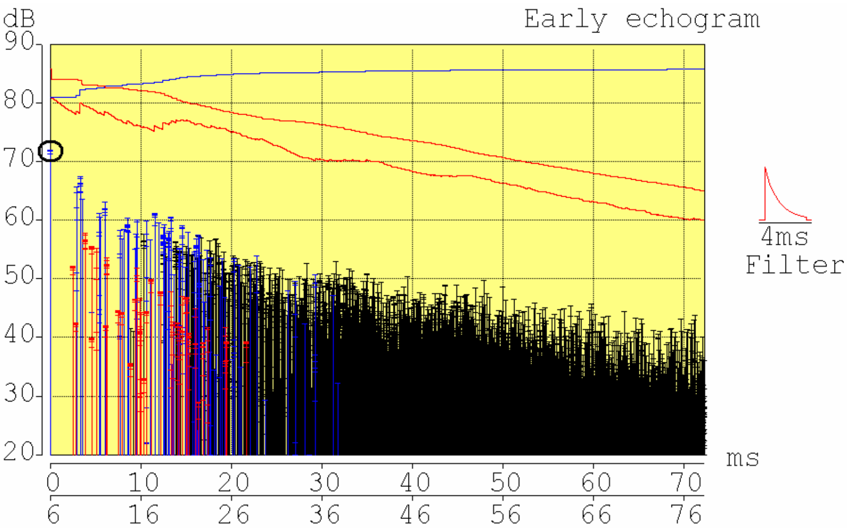


Fig. 3.38: Echogram of the Room without the step in the ceiling produced by speaker A4

3.3.2.2 Acoustic material

Broadband and Low frequency absorber

The acoustic material mainly used to optimize the simulation of the target room variation 2, namely the room without the step in the ceiling, was proposed by Thorsten Rohde. The broadband absorbers are the same as those used in Room 1 (see Section 3.3.1.2). Table 3.14 contains the corresponding absorption coefficients for the broad-band absorber and Table 3.10 for the low frequency absorber.

	125	250	500	1k	2k	4k
α	0.84	1.03	0.98	1	1	0.74

Table 3.14: Absorption coefficients of the broad-band absorber

Acoustic curtain

The acoustic curtain is the same as in Room 1 (see Section 3.3.1.2).

Acoustic ceiling

To attenuate the ceiling of Room 2, another system by KNAUF GmbH (www.knauf.at) was chosen. The exact description of the system is 'Plaza Micro M1'. Its absorption coefficients can be found in Table 3.15. Fig. 3.39 shows an example of such a tile.

	125	250	500	1k	2k	4k
α	0.40	0.50	0.65	0.60	0.60	0.55

Table 3.15: Absorption coefficients of the acoustic ceiling 'Micro M1'

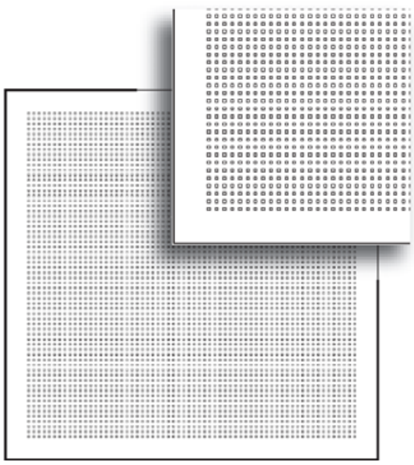


Fig. 3.39: Example picture of an acoustic ceiling tile of the type Micro M1 by KNAUF GmbH (www.knauf.at)

3.3.2.3 Placement of the absorbers

Fig. 3.40 shows the 3D view of the simulated listening Room 2 with all the acoustic material and furniture. As can clearly be see from the section above, the placement of the absorbers is the same as in Room 1, but slightly different absorbers have been used to adjust the sound field. Below a legend for the subsequent Figures can be found.

Yellow	Broadband absorbers by Trikustik
Blue	Rectangles are the low frequency absorbers. The curtain in front of the windows
Orange	Curtain in front of the windows
Red	Carpet
Turquoise	Floor
Lilac	Tables for listener and supervisor, respectively. They will be described in detail in Section 3.4.2.

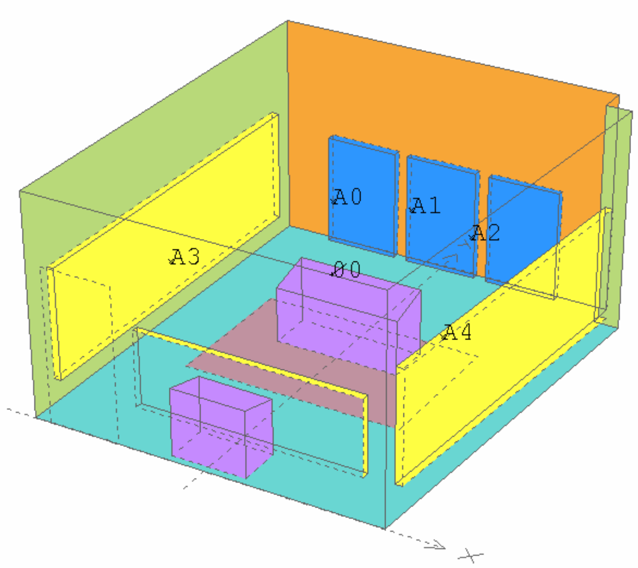


Fig. 3.40: 3D view of the fully equipped listening room, variation 2

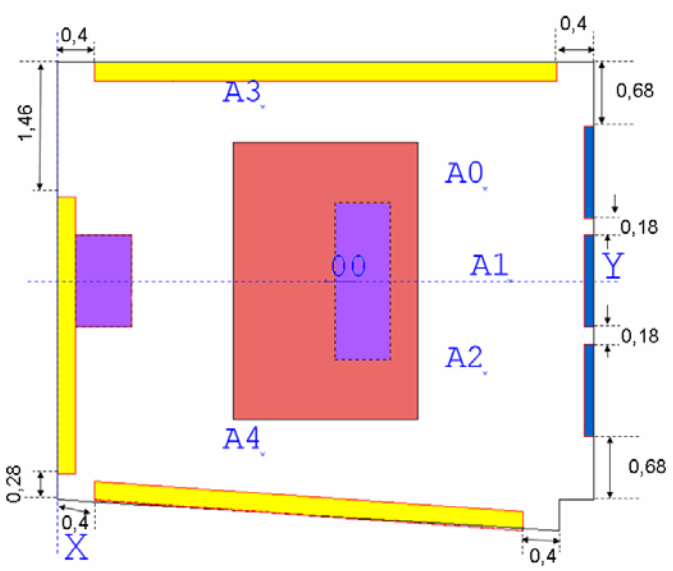


Fig. 3.41: Floor plan of the listening room without the step ceiling equipped with all necessary absorbers

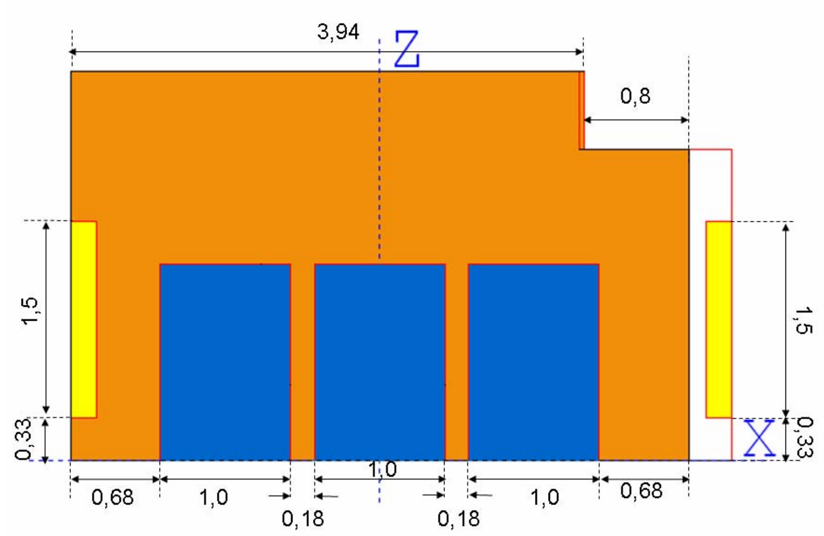


Fig. 3.42: Window perspective of the listening room without step ceiling with all necessary absorbers

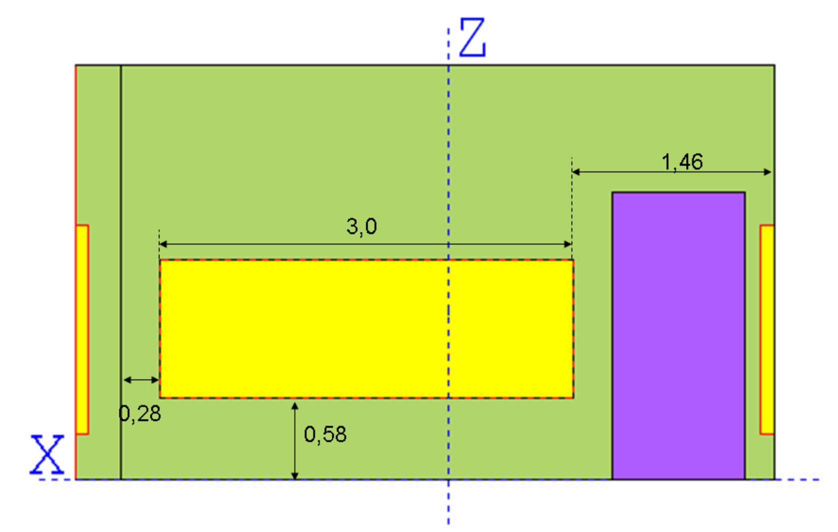


Fig. 3.43: Door perspective of the listening room without the step ceiling with all absorbers visible from this view

3.4 Sound system & furniture

The sound system and the furniture are the same in both room variations.

3.4.1 Sound system

For the purpose of an ITU-R BS 1116-1 conformant listening room, basically any high quality speakers can be used [24]. For this reason, after consulting experienced people and comparing the sound systems used in other ITU conformant listening rooms [17, 18, 19], the Genelec 1032A speakers (www.genelec.com) were selected. These have been proven to be sufficiently accurate in many listening rooms [17, 24]. Fig. 3.44 shows a photo of such a speaker.

Fig. 3.44: Example picture of a Genelec 1032A Bi-Amplified Monitor Loudspeaker

3.4.2 Furniture

Tables

The two tables presented below are special constructions brought forward by this work. Their main purpose is to be as practical as possible, concerning the stowage of possibly required electrical and other equipment.

Fig. 3.45 to Fig. 3.49 show the different views of the proposed listener table along with the most important admeasurements. Fig. 3.50 to Fig. 3.54 show the same views of the supervisor table. The turquoise square in Fig. 3.45 and Fig. 3.50 represents a computer screen that is integrated into the table top. The two cabinets of the listener table and the one of the supervisor table are meant to be used for stowing the PC(s), the audio equipment as well as electrical connections etc.

Listener Table

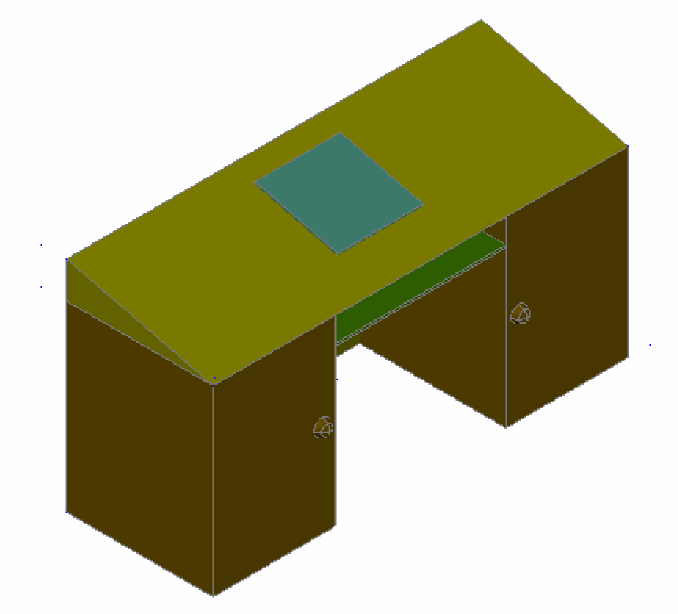


Fig. 3.45: 3D picture of the proposed listener table

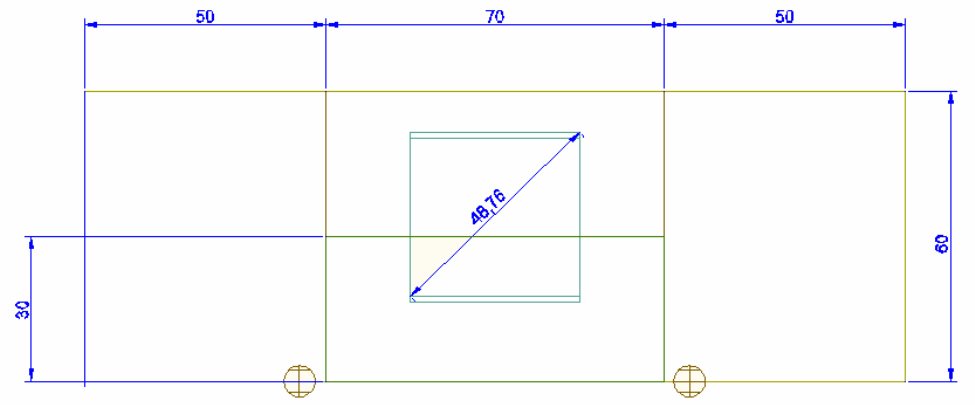


Fig. 3.46: Ground plan of the proposed listener table

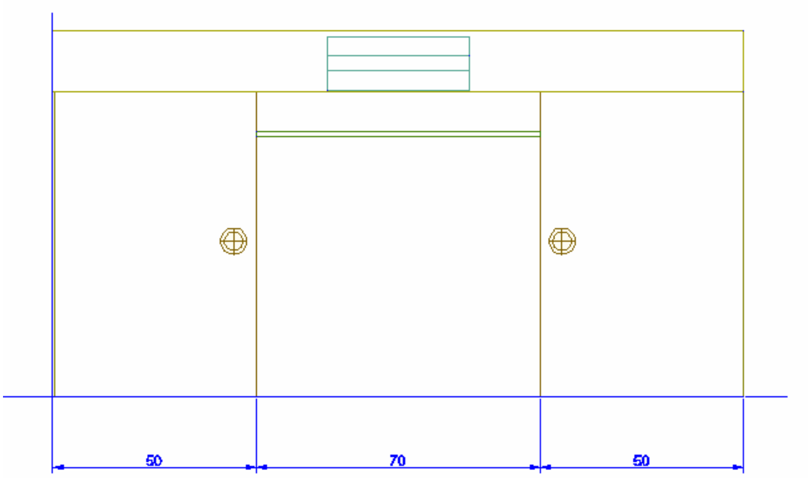


Fig. 3.47: Front elevation of the proposed listener table

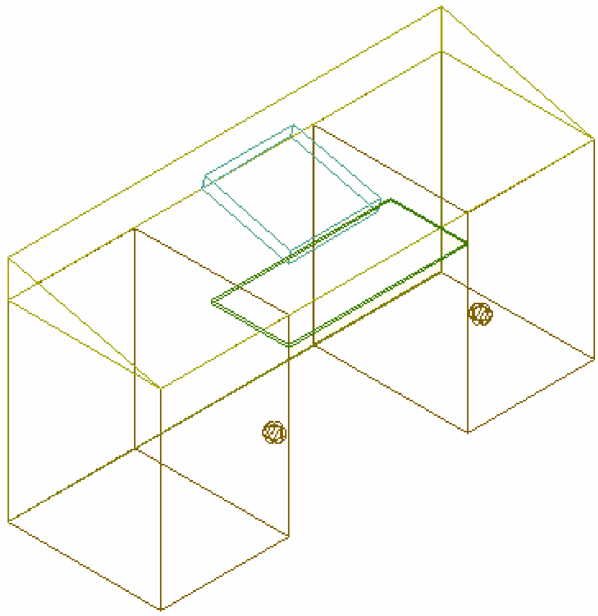


Fig. 3.48: Oblique projection of the proposed listener table

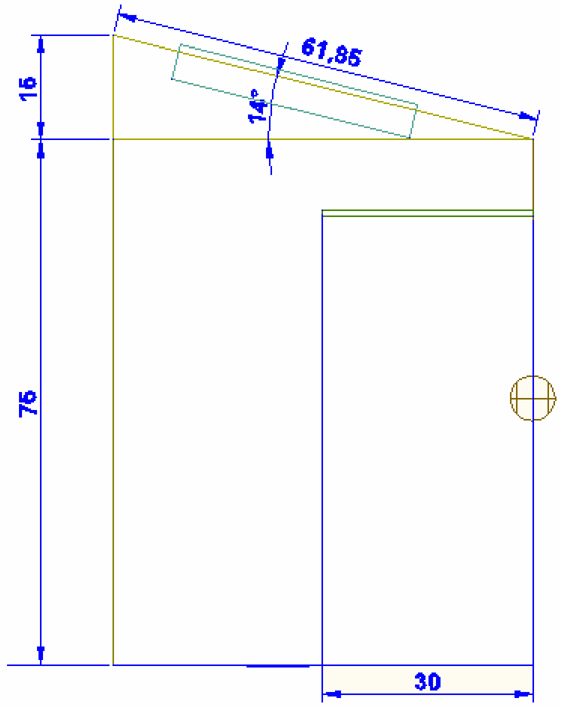


Fig. 3.49: Sheer plan of the proposed listener table

Supervisor Table

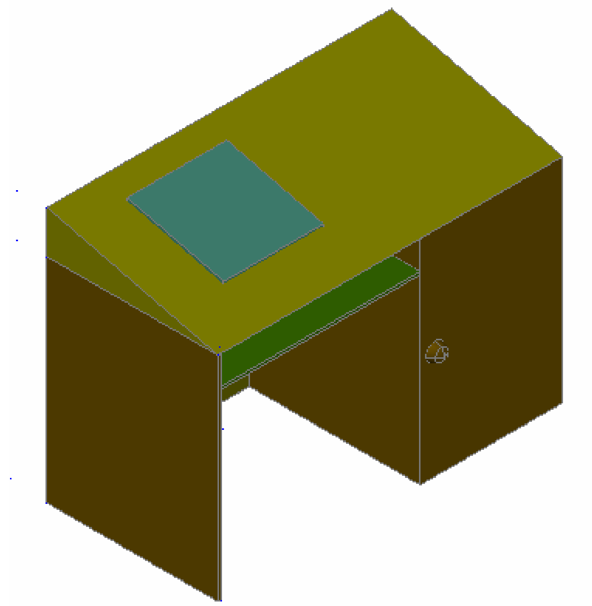


Fig. 3.50: 3D picture of the proposed supervisor table

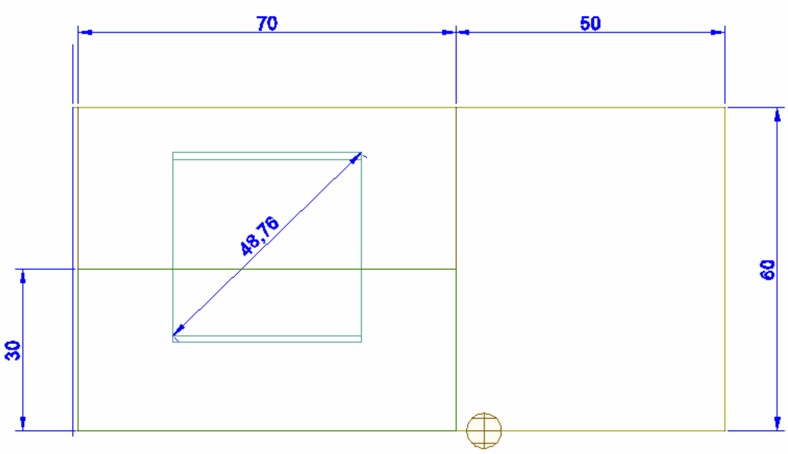


Fig. 3.51: Ground plan of the proposed supervisor table

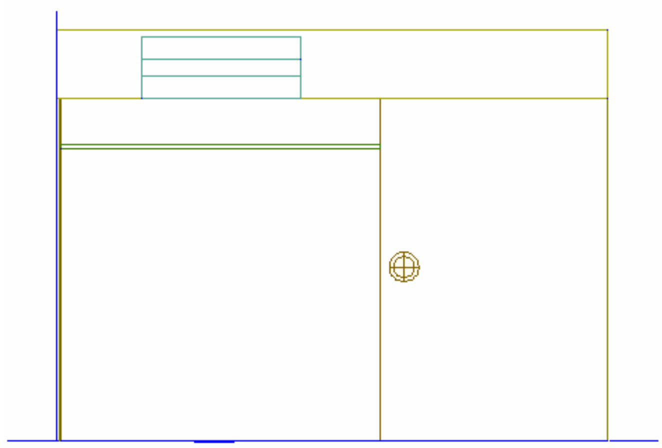


Fig. 3.52: Front elevation of the proposed supervisor table

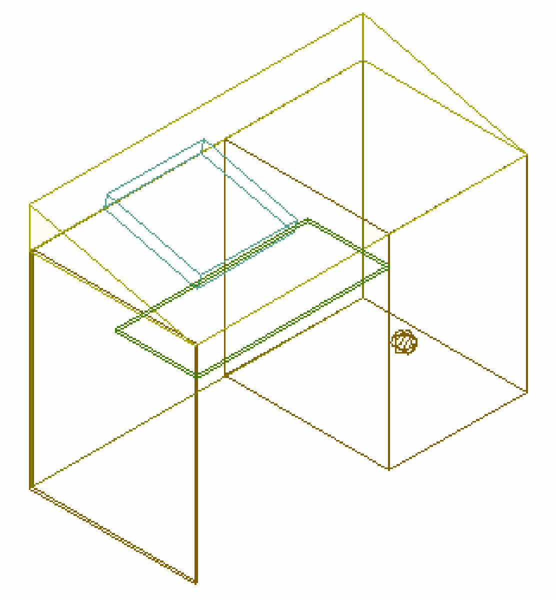


Fig. 3.53: Oblique projection of the proposed supervisor table

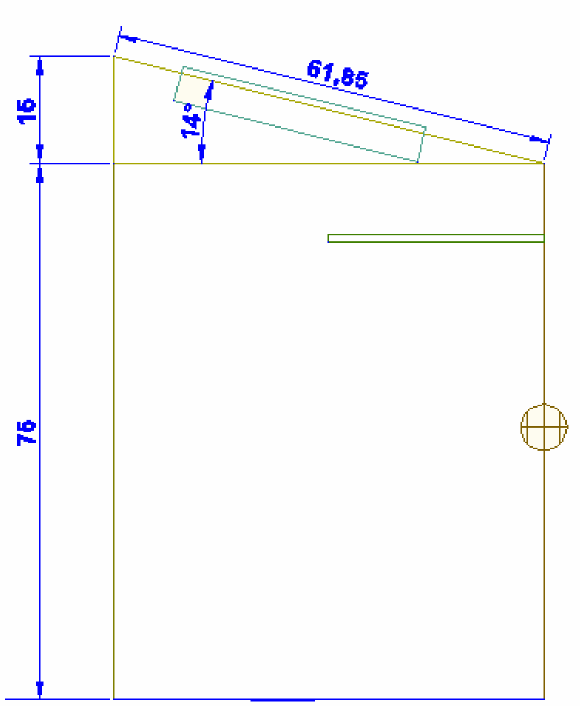


Fig. 3.54: Sheer plan of the proposed supervisor table

Chairs

The types of chairs which are chosen are acoustically not important. However, one should emphasize on finding a chair that is comfortable for the listener since feeling comfortable is of vital importance for listening tests. Such a chair could be the model 'Chicago' by Schäfer Shop GmbH (www.schaefer-shop.at), as shown in Fig. 3.55.

Fig. 3.55: Example picture of a possible chair for listener and supervisor (Schaefer Shop model 'Chicago')

Carpet

The carpet used in the listening room has two useful purposes: First, it additionally attenuates the sound field in the room, though to a minor extent. Second, and more importantly, it divides the room and indicates the 'sweet area' in front of the table. The approximate absorption coefficients for an 8 mm thick carpet that is loosely laid on the floor are stated in Table 3.16. An example picture for a carpet found at www.traumteppich.com is given in Fig. 3.56.

	125	250	500	1k	2k	4k
α	0.04	0.12	0.26	0.49	0.28	0.29

Table 3.16: Approximate absorption coefficients of the carpet

Fig. 3.56: Example picture of a carpet which could be used in the listening room (model 'Colourful summer')

3.4.3 Placement of interior

Fig. 3.57 shows the positions of each of the five loudspeakers in the listening room. The yellow dots in the grey rectangle representing the loudspeakers denote the acoustic centre of each speaker. The rectangles are not true to scale.

Fig. 3.58 shows the placements of the two tables for the listener and the supervisor, respectively, as well as the position of the carpet in the room.

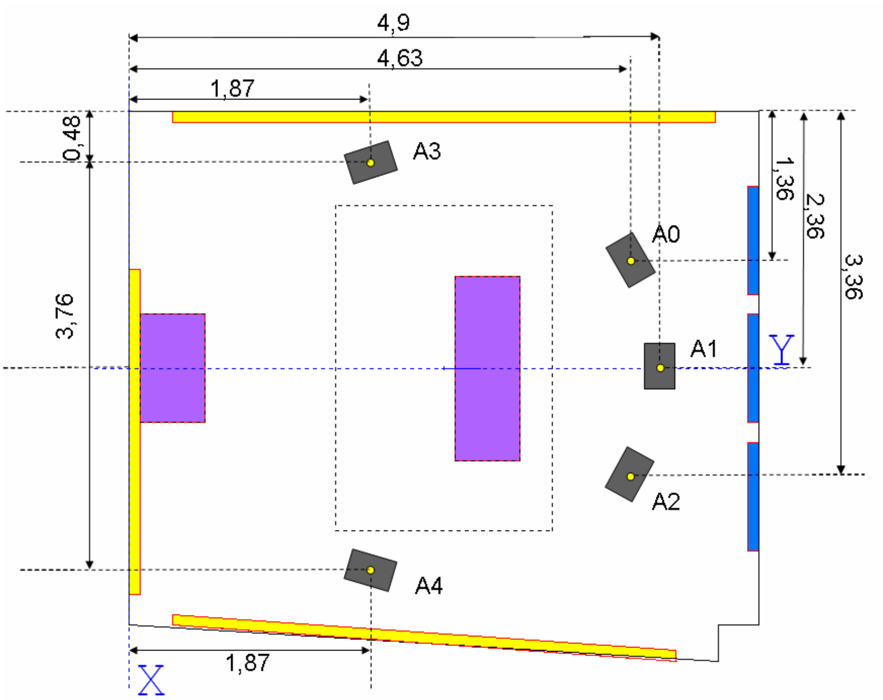


Fig. 3.57: Positioning of the loudspeaker system in the listening room

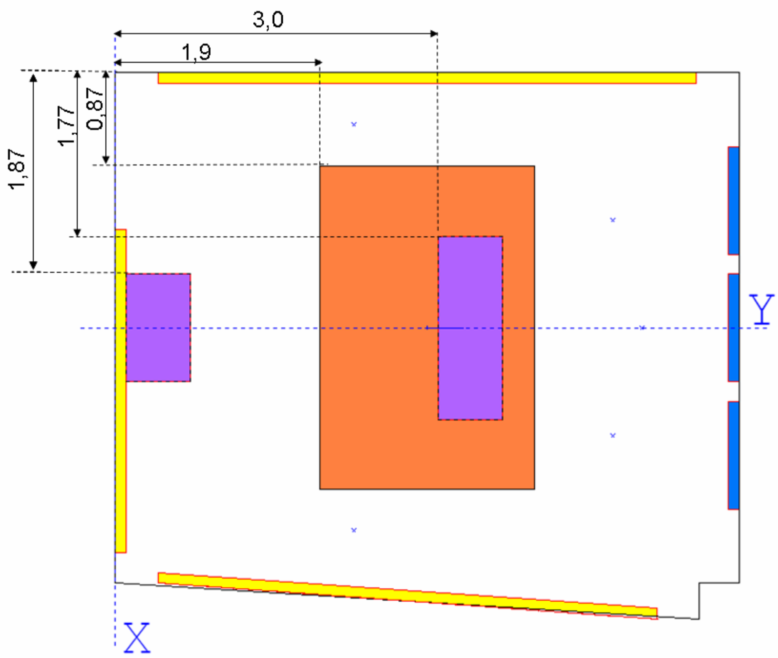


Fig. 3.58: Positioning of the carpet and the tables in the listening room

3.5 Work to accomplish

Along with the knowledge of how and where to place the necessary acoustic material, sound system and furniture, there are more aspects to the construct of the listening room which have to be considered. For example, the electronic installations now attached in the middle of the wall need to be shifted downwards in order to be able to fix the absorbers to the wall at the recommended positions. The absorbers cannot be attached further up or down the wall since this step would alter the sound field and thus the reverberation time significantly.

In addition, a mobile air conditioning device would be advisable. The room can then be air conditioned during listening test breaks and produces no noise when not working, an essential feature for listening tests. Moreover, it can be moved out of the room so as to not disturb the sound field in the small listening room and it is cheap to purchase. Whereas a permanently installed air conditioning system would cost a lot of money and raise other backdraws.

Further steps to insulate the room from outside background noise should be considered. Some of the following advisable measures were already taken into account in the Estimation of costs in Chapter 4.

- Place a second, sound insulating curtain behind the one absorbing the sound (e.g. AV32 by www.mbakustik.de)
- Replace the current windows with special sound insulating ones (e.g. Internorm 'edition 4' by www.internorm.at)
- Replace the current door with a sound insulation one (e.g. '1 Reinex 5 SP' by www.reinex.at)
- Use special silent lighting (see www.zumtobel.com)

As one could see from Sections 3.3.1.1 and 3.3.2.1 there are some early reflections that are not conformant with [1]. It should be considered and tried out whether or not any additional acoustic material could sufficiently attenuate these early reflections so as to meet the requirements in [1].

4 Estimation of costs

The prices given below for each room are mostly rounded amounts or rough estimations. However, one can get a feeling of the overall sum needed to turn the room into a proper listening room according to [1].

Please note: The calculations below do not include the working hours to turn the room into a listening room.

4.1 Room 1

Room 1	Product designation	Quantity	Price per Unit	Amount (€)
Acoustic material	Broadband absorbers R32D8 (1m*1.5m)	18 m²	€ 75,50	€ 1.359,00
	Low frequency absorbers (1m*1.5m)	3	€ 300,00	€ 900,00
	KNAUF acoustic ceiling - Tectopanel Globe G1	29 m²	€ 14,50	€ 420,00
	Acoustic curtain AV12 – mbakustik	1	€ 1.082,00	€ 1.082,00
	Rail for acoustic curtain (80 cm & 349 cm)	3.8 m	€ 13,00	€ 49,90
	Carpet 2x3 m	1	€ 402,00	€ 402,00
Sound system	Genelec 1032 Monitor Loudspeakers	5	€ 1.233,00	€ 6.165,00
	K&M 26740 Monitor tripod	5	€ 65,50	€ 327,50
	Subwoofer	1	€ 500,00	€ 500,00
Furniture	Office chair	2	€ 105,00	€ 210,00
	Listener table (estimation)	1	€ 1.000,00	€ 1.000,00
	Supervisor table (estimation)	1	€ 1.000,00	€ 1.000,00
Other equipment	Lighting (estimation)	1	€ 1.500,00	€ 1.500,00
	Sound insulation door (estimation)	1	€ 3.000,00	€ 3.000,00
	Air conditioning unit (estimation)	1	€ 500,00	€ 500,00
Sum				**€ 18.415,40**

4.2 Room 2

Room 2	Product designation	Quantity	Price per Unit	Amount (€)
Acoustic material	Broadband absorbers	12	€ 350,00	€ 4.200,00
	Low frequency absorbers	3	€ 300,00	€ 900,00
	KNAUF acoustic ceiling - Plaza Micro M1	29 m²	€ 19,50	€ 565,50
	Acoustic curtain AV12 – mbakustik	1	€ 1.082,00	€ 1.082,00
	Rail for acoustic curtain	4,75 m	€ 13,00	€ 61,75
	Carpet 2x3 m	1	€ 402,00	€ 402,00
Sound system	Genelec 1032 Monitor Loudspeakers	5	€ 1.233,00	€ 6.165,00
	K&M 26740 Monitor tripod	5	€ 65,50	€ 327,50
	Subwoofer	1	€ 500,00	€ 500,00
Furniture	Office chair	2	€ 105,00	€ 210,00
	Listener table (estimation)	1	€ 1.000,00	€ 1.000,00
	Supervisor table (estimation)	1	€ 1.000,00	€ 1.000,00
Other equipment	Lighting (estimation)	1	€ 1.500,00	€ 1.500,00
	Sound insulation door (estimation)	1	€ 3.000,00	€ 3.000,00
	Air conditioning unit (estimation)	1	€ 500,00	€ 500,00
Sum				**€ 21.413,75**

5 Summary and future prospects

The need to provide repeatable and reproducible results in listening test has greatly influenced the audio industry. Many institutions therefore have devoted themselves to finding internationally valid standards to carry out listening tests under consistent environments, no matter where. Today, a handful of such standards have settled to become generally accepted and used.

In the course of this project, a listening room has been specified that, when finished, should meet the requirements of tone of the currently available standards. The current standards that were presented in this work were published by the ITU, International Telecommunication Union, the EBU, European Broadcasting Union, the AES, Audio Engineering Society and the Nordic Broadcasting Companies. These standards were compared and after validating each of them, the ITU-R BS 1116-1 [1] standard was chosen to be the most suitable. This choice was mainly made due to the limited space available (~30 m²) in the target room which the standard still accepted to be suitable for multichannel sound reproduction.

At the beginning of the specification, a historical outline of already existing listening rooms that have been built at various locations in Europe over the last 20 years has been given. With this knowledge first ideas to possible approaches for the concept and construction of a listening room were provided. Later in the work, the construction process greatly took profit from the experience of those people who were contacted and who for instance gave their advice on which sound system to use.

With the historical background in mind and the most suitable standard chosen, the realization process could begin. First, the boundary conditions were laid out in order to show the existing state. A detailed floor plan and pictures of the empty room were given.

The simulation of the room was implemented in the commercially available software CATT Acoustic®. Since the target room had a step in the ceiling and as it was not sure if this step would incur problems in the sound field, an alternative approach omitting the step was also implemented in CATT.

To be able to correctly simulate the sound field of the room, the simulation had to be calibrated first. Therefore, a thorough acoustic measurement of the room was carried out. With the help of the commercially available software WinMLS, a dodecahedron loudspeaker as a sound source and 16 measuring points, the room's acoustics was captured. The parameters, that were measured, were the reverberation time T30 and the Clarity C80 from which the average values were calculated. With these , the simulation was calibrated afterwards which took far more time than at first expected. To calibrate the simulation correctly with the C80 values obtained by the measurement with WinMLS proved to be quite impossible. The obtained values were in such a high or low range, that CATT could not reproduce them. Nevertheless the work was continued with the imperfect calibration since the reverberation time was the most important indicator for the calibration. The calibration of the reverberation time T30 was very exact, with a maximal deviation of 0.01 s.

With the calibration finished, the optimization process could be started. For this, acoustic material from several companies was tried out in the simulation until the best combination, which yielded the desired acoustic values, was found. The task was more difficult than presumed, since a large variety of different absorbers exist. An advantage to the work was that the sound field needed only to be attenuated according to the ITU standard's recommendation. The process of finding the optimal room equipment was not explicitly described in the written report, only the acoustic material found to be optimal. A list of the material was given along with a detailed plan of the placement of the absorbers, for each room variation a different fixture. The results for both approaches of the room's geometry were both surprisingly good. The reverberation time results were all within the limits recommended by the standard, except for minor variances which could be neglected. Furthermore, the given budget limit was kept. Finally, it can be said that the results obtained by the simulation are very satisfactory.

Even so, the proposed room with its interior could not meet all of the limits the standard of choice has stated. The initial floor area of the target room was marginal for multichannel applications. The minimum speaker-to-listener distance could not be maintained simultaneously with the minimum speaker-to-wall distance. This fact proved to be problematic because of the room proportions. Further, the early reflections could not be attenuated sufficiently according to [1]. Finally, the background noise possibly could exceed the limits at times.

Thus, some additional steps will have to be taken to complete the listening room proposed in this work. It will have to be considered to replace the door and windows with sound insulating ones, apply silent lighting and an air conditioning unit. Moreover, the problem of the early reflections should be taken care of. This could happen by applying some more absorbing material at critical points and smaller surfaces (as described in Sections 3.3.1.1 and 3.3.2.1) while at the same time maintaining the already existing, standard conformant sound field in the room.

With the optimization completed, the room now needs to be equipped according to the recommendations given in the Sections above. The decision for the choice of one of the two variations relies with JOANNEUM RESEARCH. From a scientific point of view, both are suitable for performing the tasks, specified at the beginning of the work.

After the room variation chosen is equipped another series of thorough measurement of the actual sound field of the listening room will be necessary in order to verify whether or not the sound field is consistent with the predictions by CATT. Not until this has been checked can the room really be put into operation. Future will show how good the values of the simulation will fit the final real sound field after the construction has been accomplished. If any coarse deviations of the predicted values should occur (that are obviously not due to measuring inaccuracies), structural measures will have to be taken in order to correct these possible errors.

6 Bibliography

[1] ITU-R. Recommendation BS 1116-1, Methods for the Subjective Assessment of Small Impairments in Audio Systems Including Multichannel Sound Systems. International Telecommunication Union Radiocommunication Assembly, 1997.

[2] ISHII Shinichiro, MIZUTANI Toshiyuki: *A New Type of Listening Room and its Characteristics – A Proposal for a Standard Listening Room.* Audio Engineering Society 72nd Convention, Anaheim, October 1982

[3] BORENIUS Juhani, KORHONEN Seppo: *New Aspects on Listening Room Design.* Audio Engineering Society 77th Convention, Hamburg, March 1985

[4] STEINKE Gerhard: *Minimum Requirements for Reference Listening Rooms*. Audio Engineering Society 84th Convention, Paris, March 1988

[5] JÄRVINEN A., SAVIOJA L., MÖLLER H., IKONEN V., RUUSUVUOR A.: *Design of a Reference Listening Room – A Case Study.* Audio Engineering Society 103rd Convention, New York, September 1997

[6] ARATO-BORSI Eva: *New Reference listening Room for Two-Channel and Multichannel Stereophonic.* Audio Engineering Society 104th Convention, Amsterdam, May 1998

[7] WALKER Robert: *A Controlled-reflection Listening Room for Multichannel Sound.* Audio Engineering Society 104th Convention, Amsterdam, May 1998

[8] HOEG Wolfgang: *Listening Conditions for Subjective Assessment of Sound Quality: the Status of International Standardisation.* Audio Engineering Society 96th Convention, Amsterdam, February 1994

[9] WALKER R.: *A New Approach to the Design of Control Room Acoustics for Stereophony.* Audio Engineering Society 94th Convention, Berlin, March 1993

[10] WALKER R.: *Controlled Image Design: The management of stereophonic image quality.* BBC Research Report No. 1995/4

[11] WALKER R.: *Early Reflections in Studio Control Rooms: the Results from the First Controlled Image Installation.* Audio Engineering Society 96th Convention, Amsterdam, February 1994

[12] WALKER R.: *Controlled Image Design: Results from the First Installation.* BBC Research Report No. 1995/5

[13] BECH Søren, ZACHAROV Nick: *Perceptual Audio Evaluation.* Wiley, 2006

[14] EBU. *Technical Document Tech 3276: Listening Conditions for the Assessment of Sound Programme Material: Monophonic and Two-Channel Sound.* European Broadcasting Union, May 1998

[15] EBU. *Technical Document Tech 3276: Listening Conditions for the Assessment of Sound Programme Material: Multi-Channel Sound.* European Broadcasting Union, February 1999

[16] BAIRD, M.D.M.: *A Wideband Absorber for Television Studios.* BBC Research Report No 1994/12

[17] NAQVI Amber, RUMSEY Francis: *The Active Listening Room Simulator: Part 1.* Audio Engineering Society 110th Convention, Amsterdam, May 2001

[18] NAQVI Amber, RUMSEY Francis: *The Active Listening Room Simulator: Part 2.* Audio Engineering Society 112th Convention, Munich, May 2002

[19] NAQVI Amber, RUMSEY Francis: *The Active Listening Room Simulator: Part 3.* Audio Engineering Society 112th Convention, Munich, May 2002

[20] ZOLLNER, M. and ZWICKER E.: *Elektroakustik.* Springer 1993, 3.Auflage

[21] CATT, Mariagatan 16A, SE-41471 Gothenburg, SWEDEN; WWW: *http://www.catt.se/*

[22] HOEG Wolfgang: *Oral Information*

[23] GRABER G, WESELAK W: *Raumakustik VO*, *Version 3.0.* TU Graz, Institut für Breitbandkommunikation, SS 2004

[24] KOIVUNIEMI Kalle: *Oral Information*

Appendix A

Detailed results of the empty room measurements

The following Sections give the exact values of reverberation time T30 and clarity C80 produced by each of the source positions as was measured in the target room.

Source Position 1

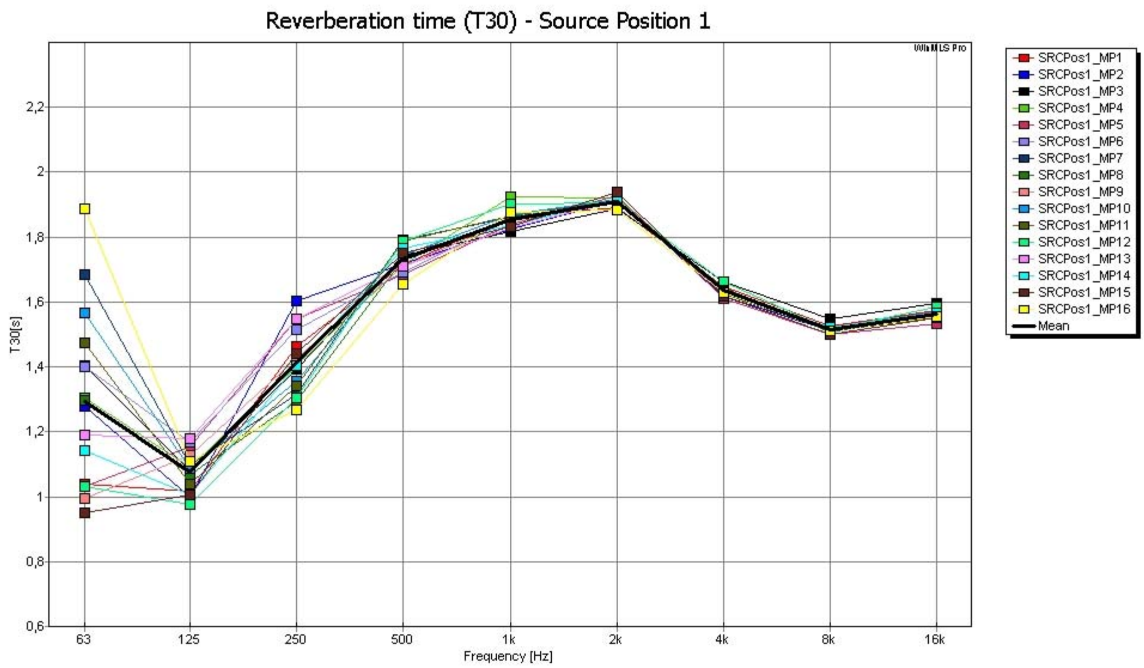
Reverberation Time T30

[Hz]	MP1	MP2	MP3	MP4
63	1.038	1.279	1.404	1.306
125	1.016	0.999	1.080	1.092
250	1.462	1.604	1.393	1.404
500	1.714	1.719	1.742	1.714
1000	1.860	1.825	1.818	1.924
2000	1.891	1.914	1.886	1.921
4000	1.648	1.619	1.662	1.637
8000	1.526	1.510	1.547	1.520
16000	1.575	1.555	1.595	1.559

[Hz]	MP5	MP6	MP7	MP8
63	1.032	1.399	1.683	1.297
125	1.154	1.170	1.096	1.069
250	1.549	1.514	1.317	1.293
500	1.686	1.693	1.792	1.731
1000	1.841	1.854	1.862	1.849
2000	1.927	1.914	1.906	1.909
4000	1.612	1.642	1.631	1.643
8000	1.500	1.514	1.522	1.508
16000	1.532	1.556	1.569	1.564

[Hz]	MP9	MP10	MP11	MP12
63	0.993	1.566	1.473	1.031
125	1.126	1.086	1.039	0.977
250	1.427	1.355	1.343	1.305
500	1.712	1.744	1.787	1.787
1000	1.853	1.870	1.865	1.901
2000	1.906	1.915	1.914	1.906
4000	1.635	1.633	1.626	1.661
8000	1.517	1.522	1.511	1.516
16000	1.556	1.568	1.551	1.585

[Hz]	MP13	MP14	MP15	MP16
63	1.190	1.142	0.950	1.889
125	1.179	1.005	1.005	1.109
250	1.547	1.405	1.441	1.268
500	1.711	1.767	1.752	1.656
1000	1.828	1.836	1.831	1.876
2000	1.913	1.916	1.937	1.883
4000	1.637	1.634	1.617	1.630
8000	1.516	1.523	1.500	1.510
16000	1.566	1.567	1.553	1.556



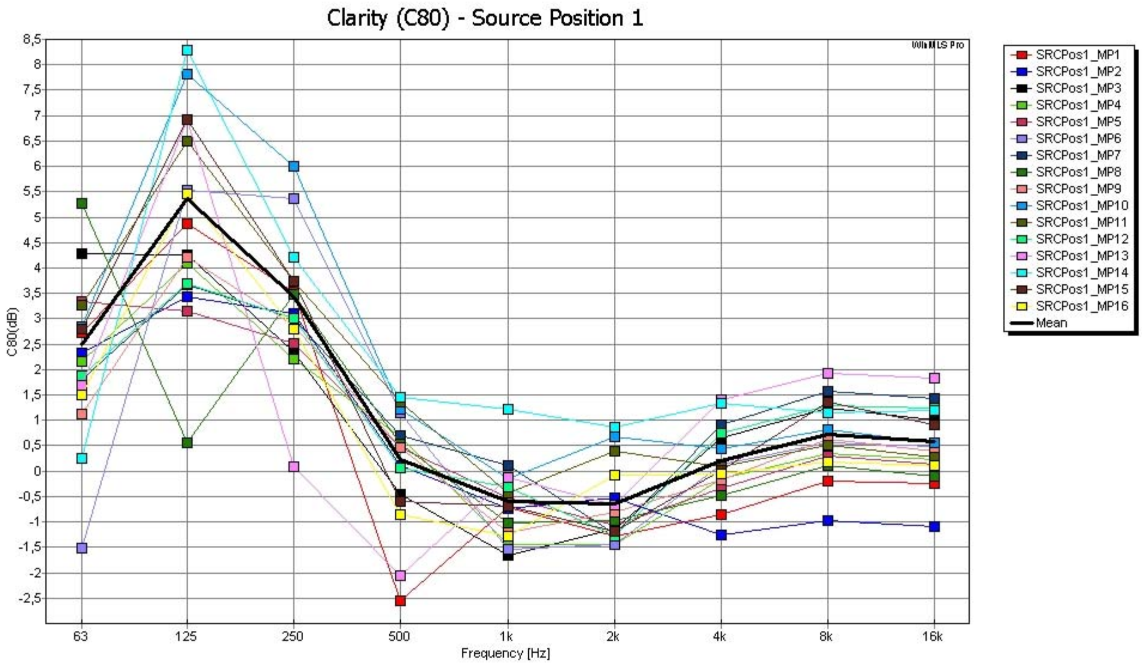
Clarity C80

[Hz]	MP1	MP2	MP3	MP4
63	2.717	2.327	4.282	2.170
125	4.863	3.430	4.249	4.105
250	3.531	3.111	2.346	2.202
500	-2.564	0.104	-0.462	0.670
1000	-0.715	-0.738	-1.655	-1.438
2000	-1.283	-0.517	-1.150	-1.442
4000	-0.865	-1.263	0.650	-0.153
8000	-0.194	-0.974	1.250	0.346
16000	-0.251	-1.084	0.997	0.232

[Hz]	MP5	MP6	MP7	MP8
63	3.330	-1.513	1.796	5.269
125	3.143	5.532	3.659	0.550
250	2.514	5.356	3.009	3.477
500	0.474	1.150	0.711	0.536
1000	-0.526	-1.542	0.112	-1.020
2000	-1.062	-1.449	-1.221	-0.968
4000	-0.346	0.133	0.907	-0.488
8000	0.301	0.559	1.566	0.102
16000	0.135	0.484	1.440	-0.097

[Hz]	MP9	MP10	MP11	MP12
63	1.135	2.833	3.263	1.888
125	4.219	7.807	6.489	3.688
250	2.862	6.007	3.742	3.011
500	0.467	1.224	1.364	0.059
1000	-1.205	-0.141	-0.440	-0.310
2000	-0.804	0.670	0.397	-1.284
4000	-0.162	0.443	0.099	0.748
8000	0.629	0.822	0.501	1.299
16000	0.400	0.565	0.270	1.247

[Hz]	MP13	MP14	MP15	MP16
63	1.695	0.241	2.806	1.508
125	6.916	8.289	6.927	5.452
250	0.084	4.219	3.744	2.804
500	-2.060	1.449	-0.595	-0.861
1000	-0.114	1.228	-0.695	-1.284
2000	-0.663	0.860	-1.192	-0.074
4000	1.418	1.337	0.024	-0.051
8000	1.924	1.139	1.364	0.190
16000	1.831	1.189	0.922	0.101


Clarity (C80) - Source Position 1
WinMLS Pro
C80(dB)
Frequency [Hz]
63
125
250
500
1k
2k
4k
8k
16k
8,5
8
7,5
7
6,5
6
5,5
5
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
-0,5
-1
-1,5
-2
-2,5
SRCPos1_MP1
SRCPos1_MP2
SRCPos1_MP3
SRCPos1_MP4
SRCPos1_MP5
SRCPos1_MP6
SRCPos1_MP7
SRCPos1_MP8
SRCPos1_MP9
SRCPos1_MP10
SRCPos1_MP11
SRCPos1_MP12
SRCPos1_MP13
SRCPos1_MP14
SRCPos1_MP15
SRCPos1_MP16
Mean

Source Position 2

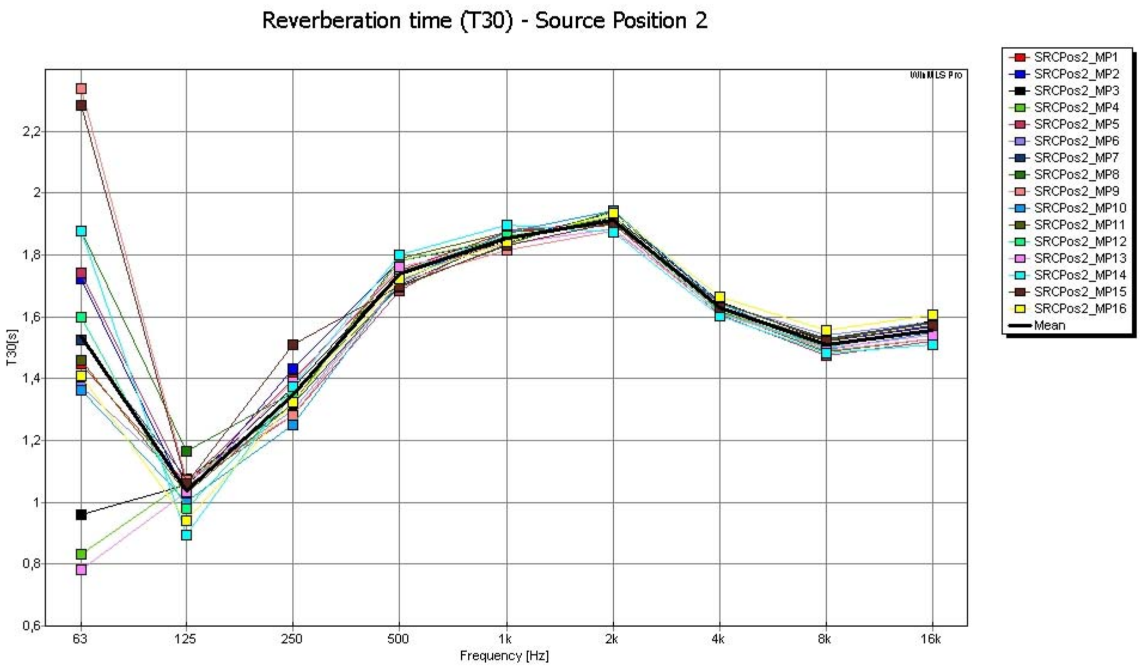
Reverberation Time T30

[Hz]	MP1	MP2	MP3	MP4
63	1.448	1.724	0.961	0.833
125	1.060	1.023	1.059	1.067
250	1.398	1.430	1.369	1.318
500	1.750	1.781	1.744	1.782
1000	1.872	1.851	1.843	1.854
2000	1.913	1.936	1.924	1.923
4000	1.629	1.650	1.649	1.618
8000	1.512	1.521	1.521	1.499
16000	1.552	1.568	1.586	1.539

[Hz]	MP5	MP6	MP7	MP8
63	1.743	1.373	1.524	1.877
125	1.055	1.064	1.077	1.164
250	1.283	1.299	1.315	1.356
500	1.685	1.714	1.703	1.697
1000	1.880	1.861	1.856	1.837
2000	1.900	1.904	1.907	1.941
4000	1.606	1.641	1.647	1.620
8000	1.474	1.540	1.531	1.487
16000	1.523	1.582	1.583	1.529

[Hz]	MP9	MP10	MP11	MP12
63	2.338	1.364	1.460	1.600
125	1.073	1.004	1.030	0.978
250	1.281	1.249	1.320	1.343
500	1.714	1.716	1.788	1.745
1000	1.814	1.872	1.873	1.862
2000	1.878	1.943	1.898	1.909
4000	1.626	1.645	1.646	1.612
8000	1.489	1.493	1.523	1.503
16000	1.529	1.549	1.577	1.560

[Hz]	MP13	MP14	MP15	MP16
63	0.781	1.879	2.284	1.408
125	1.032	0.895	1.061	0.940
250	1.388	1.376	1.509	1.324
500	1.760	1.798	1.701	1.721
1000	1.836	1.898	1.829	1.844
2000	1.886	1.872	1.904	1.937
4000	1.610	1.604	1.632	1.664
8000	1.497	1.484	1.520	1.556
16000	1.540	1.512	1.572	1.608



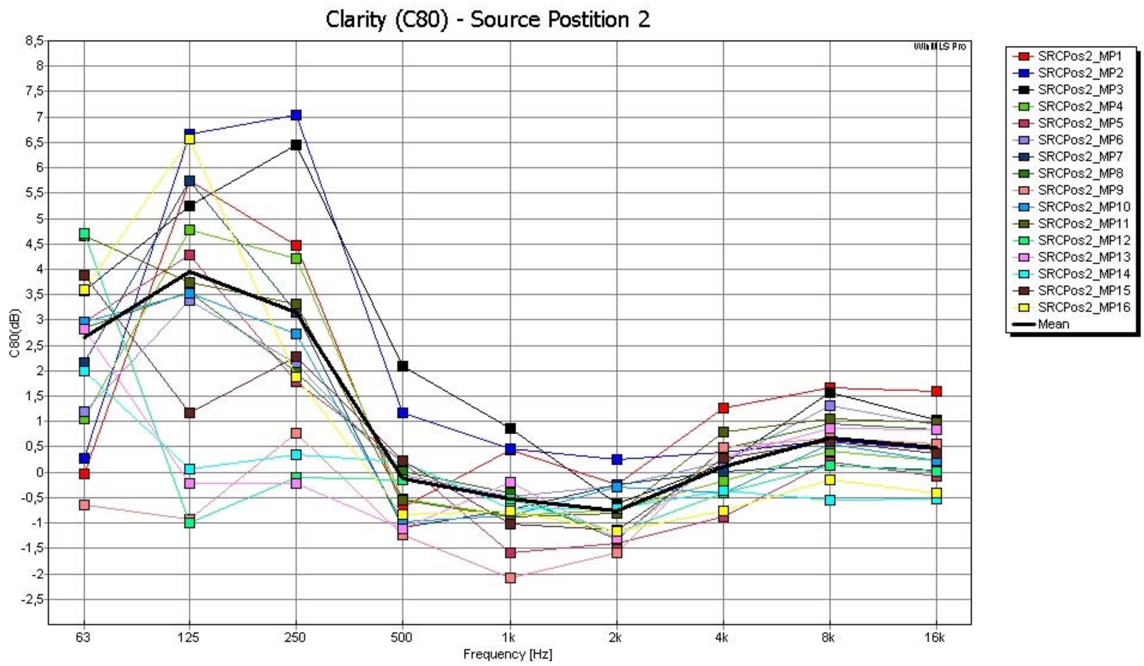
Clarity C80

[Hz]	MP1	MP2	MP3	MP4
63	-0.034	0.275	3.580	1.060
125	5.738	6.669	5.253	4.786
250	4.475	7.032	6.439	4.210
500	-0.685	1.166	2.085	-0.526
1000	0.448	0.456	0.868	-0.852
2000	-0.251	0.252	-0.610	-0.742
4000	1.271	0.400	0.147	-0.174
8000	1.671	0.640	1.576	0.417
16000	1.590	0.452	1.034	0.234

[Hz]	MP5	MP6	MP7	MP8
63	2.972	1.193	2.167	2.836
125	4.279	3.383	5.742	3.560
250	1.773	2.149	3.141	1.969
500	0.212	-0.060	-1.086	0.025
1000	-1.581	-0.488	-0.728	-0.409
2000	-1.400	-0.255	-0.252	-1.331
4000	-0.889	0.213	0.025	0.460
8000	0.211	1.316	0.123	0.961
16000	-0.082	0.943	0.041	0.840

[Hz]	MP9	MP10	MP11	MP12
63	-0.638	2.959	4.649	4.702
125	-0.933	3.534	3.742	-1.006
250	0.770	2.719	3.318	-0.097
500	-1.224	-0.967	-0.552	-0.144
1000	-2.088	-0.848	-0.884	-0.514
2000	-1.595	-0.300	-0.803	-1.175
4000	0.484	-0.397	0.795	-0.409
8000	0.683	0.550	1.057	0.146
16000	0.560	0.230	0.991	0.012

[Hz]	MP13	MP14	MP15	MP16
63	2.820	1.994	3.885	3.610
125	-0.209	0.066	1.172	6.567
250	-0.228	0.342	2.290	1.872
500	-1.115	0.198	0.232	-0.835
1000	-0.195	-0.707	-1.012	-0.756
2000	-1.314	-0.711	-1.132	-1.172
4000	0.305	-0.372	0.278	-0.764
8000	0.856	-0.554	0.596	-0.157
16000	0.831	-0.524	0.378	-0,396



Appendix B

ITU-R BS 1116-1

For the full version of the standard ITU-R BS 1116-1 *‘Methods for the subjective assessment of small impairments in audio systems including multichannel sound systems’* please turn page.